GILBERT FIELDER

Structure of the Moon's Surface

PERGAMON PRESS

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GILBERT FIELDER

Fellow of the Royal Astronomical Society

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This important and intensely interesting volume brings together all that is known about the Moon, and is based on a great amount of pertinent observational data which the author has assembled and studied. From it he has produced a largely unprejudiced text which brings lunar studies up to date and stresses the importance of certain features of the Moon which have frequently been disregarded in the past, largely because of lack of knowledge of them.

Part I reviews and summarizes important physical problems; and relatively new facts or ideas, which have been insufficiently emphasized in the past, are discussed in Part II.

In the final chapter, on the origin of the surface structure of the Moon, the textbook style is maintained in so far as the conclusions are based on facts drawn from the rest of the book, and hence do not favour any particular theory. Reference lists are provided at the end of each chapter, and the author has consulted virtually all these works.

This book will be of use both to the professional scientist and to the amateur lunar astronomer.

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Frontispiece

JEREMIAH HORROCKS' OBSERVATORY,
MOOR PARK, PRESTON.

STRUCTURE OF THE MOON'S SURFACE

by GILBERT FIELDER
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SET IN TIMES NEW ROMAN BY SANTYPE LTD., SALISBURY
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TO MY PARENTS

Through whose help and encouragement I have found it possible to write this book.

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List of Abbreviations *

A.J.: Astronomical Journal.
A.N.: Astronomische Nachrichten.
Ap. J.: Astrophysical Journal.
B.S.A.F.: Bulletin de la Société Astronomique de France.
C.R.Acad. Sci.: Comptes Rendus d'Academie de Science.
J.B.A.A.: Journal of the British Astronomical Association.
J.I.L.S.: Journal of the International Society.
J.R.A.S. Can.: Journal of the Royal Astronomical Society of Canada.
J.R.N.B.S.: Journal of Research of the National Bureau of Standards.
Mem. B.A.A.: Memoirs of the British Astronomical Association.
Mem. R.A.S.: Memoirs of the Royal Astronomical Society.
M.N. Geo. Supp.: Monthly Notices of the Royal Astronomical Society; Geophysical Supplement.
M.N. (R.A.S.): Monthly Notices of the Royal Astronomical Society.
Nat.: Nature.
N.Z.J. Sci. Tech.: New Zealand Journal of Science and Technology.
P.A.S.P.: Publications of the Astronomical Society of the Pacific.
Proc. Phys. Soc.: Proceedings of the Physical Society.
Trans. I.A.U.: Transactions of the International Astronomical Union.

* Abbreviations are used in the references given at the end of each chapter; this list does not include all those abbreviations which are thought to be intelligible in themselves.

Foreword

A GREAT amount of pertinent observational data has been gathered about the Moon and the aim of this book is to assemble and marshal the relevant matter, and to produce a largely unprejudiced text which brings lunar studies up to date and stresses the importance of certain features of the Moon which have frequently been disregarded in the past, largely because of lack of knowledge of them. In his book *The Face of the Moon*, Dr. Ralph B. Baldwin collected a vast amount of data on craters, both terrestrial and lunar, and he dealt in an excellent manner with the problems immediately related to the impact origin of the lunar craters. J. E. Spurr's *Geology Applied to Selenology* deals exhaustively—but solely—with an igneous type of theory.

Theories such as these find but brief mention in this book: Part I reviews and summarizes important physical problems; and relatively new facts or ideas, which have been insufficiently emphasized in the past, are discussed in Part II.

Chapter I is merely a note on what is, in reality, a complicated and difficult subject. It was thought desirable to mention some of the principal facts concerning the motion of the Moon in order that subsequent discussions might be more easily understood.

In the final chapter, on the origin of the surface, the textbook style is maintained in so far as the conclusions are based on facts drawn from the rest of the book, and hence do not favour any particular pre-existing theory. Reference lists are provided at the end of each chapter, and the author has consulted virtually all these works.

It is hoped that this book will be of use both to the professional scientist and to the amateur lunar astronomer.

Note: Attention is drawn to the Key Chart at the end of this book. This Chart identifies features discussed in the text.

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All the photographs in this book which are not otherwise acknowledged were taken in 1956 at the Pic-du-Midi Observatory, by kind permission of the Director of the Observatory, Dr. J. Rösch, and I should like to thank him for allowing me the privilege to work at his Observatory. Figures 2-3-3b and 2-3-7a have been based on work supported by the Geophysics Research Directorate of the U.S. Air Force Cambridge (Mass.) Research Centre, through the European Office of the A.R.D.C., Brussels. I am very much indebted to Dr. R. W. O. Kurth, who read and criticised a large part of my original typescript.

G.F.

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Part I

CHAPTER 1

The Librations of the Moon

1-1. Note on the orbit of the Moon

A study of the involved "lunar theory"—the theory of the motion of the Moon—has been presented by Brown (1896; 1899a; 1899b; 1905; 1910). The most important force governing the motion of the Moon relative to the Earth is the gravitational attraction of the Earth. If the Earth–Moon system could be isolated, then the Moon's path would approximate to an ellipse with the centre of the Earth close to one focus of the ellipse. Together with other gravitational forces, the attraction of the Sun, which differs for the Earth and the Moon at different times, upsets the comparative perfection of this ideal two-body system. This causes a variation in the eccentricity of the Moon's orbit. The mean distance of the Moon from the Earth is about 384,400 km (238,900 miles), and the variation of the distance between the Earth and the Moon (from 363,000 km to 406,000 km) causes the Moon to appear bigger and brighter than average at certain times.

1-2. The librations of the Moon

Three quite empirical laws governing the motion of the Moon were proposed by D. Cassini. These are:

(i) The Moon is a synchronous satellite which rotates at a uniform rate about an axis which is fixed with respect to the Moon. "Synchronous" means that the orbital and axial periods of rotation of the Moon are equal and, hence, that a terrestrial observer may see only one half of the Moon's surface.

(ii) The inclination of its axis of rotation to the ecliptic (the plane of the Earth's orbit) is invariable.

(iii) The normal to the ecliptic and the normal to the plane of the Moon's orbit, both passing through the centre of the Earth, always lie in a plane which contains the axis of the rotation of the Moon.

These are only approximate laws: the apparent centre of the Moon's disk is not a fixed point on the Moon's surface, and the wanderings of such a point from the apparent centre constitute the lunar libration. The observed libration is called the *total* or *apparent libration*. It is made up of several terms, and these can be grouped under one or other of the headings "*optical librations*" and "*physical*" or "*real*" librations. The components of the optical libration are the *optical libration in longitude* for a geocentric observer, which is due to the irregular motion of the Moon in its orbit combined with its more uniform axial angular velocity, the *optical libration in latitude* for a geocentric observer, which is due to the inclination of the Moon's orbit and axis to the ecliptic, the *diurnal libration*, which arises because the observer is displaced from the centre of the Earth, and the *parallactic libration*. The last-mentioned quantity depends on the absolute distance of the Moon from the observer, for he views the Moon as a conical projection (Fig. 1-2-1), and hence he sees more

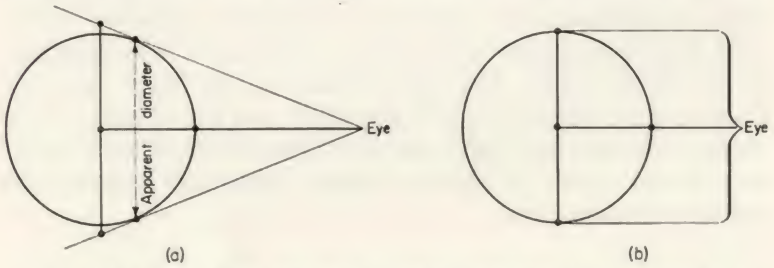

FIG. 1-2-1. The Moon seen in (a) conical projection; (b) orthographic projection

of the surface when the Moon's distance is greatest. An illustration of the effect produced by the diurnal libration has been presented by Kristenson (1954) who has plotted the lunar profile, in seconds of arc, for the region bounded by position angles* 10° and 350°, for (a) an observer in Canada, (b) an observer in southern Sweden, and (c) an observer situated in Iran. The differences in the profiles are due to the differing positions of the various observers.

A short-period component of the fading of radio echoes from the Moon was detected by Kerr, Shain, and Higgins, in 1949, and was confirmed by Browne, Evans, Hargreaves, and Murray (1956) on a wavelength of 2·5 m. Such fading was explained by assuming that

* See p. 9.

the Moon behaved like a number of discrete reflectors in relative motion, the continual phase-changes of the reflected signals causing the intensity of the echo to vary at a rate proportional to the rate of librating.

The physical libration, made up of a forced component and a very small free component, is due to the form of the Moon itself (see 3-1), which results in the Moon having an angular velocity which is not quite constant. The maxima physical librations in longitude and in latitude are very much smaller than the corresponding maxima in the optical librations.

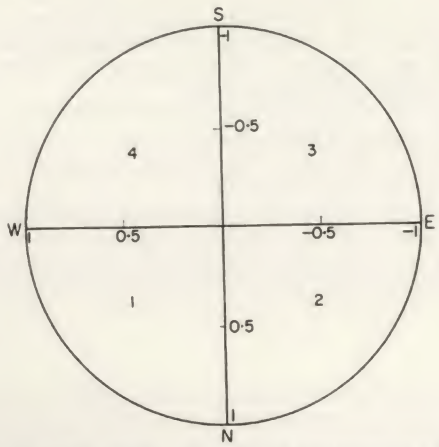

FIG. 1-2-2. The Cardinal Points and Quadrants of the Moon

The optical librations are of the greatest importance, for without them we would have practically no knowledge of the manner in which the shape of the Moon departs from that of a sphere. A further, but much less important consequence of the librational movements, is that the terrestrial observer may see slightly more than half of the surface formations. Study of a feature which is situated close to the mean limb may thus generally be pursued with greater profit when the libration for that feature is extreme and favourable.

In the astronomical telescope, every point on the Moon is inverted. According to convention, south is at the top, north is at the bottom, east to the right, and west to the left, as shown in Fig. 1-2-2. The flat projection of the Moon has been divided in the conventional manner into four quadrants, each one isolated by means of rectangular

axes. All points in the first quadrant have positive Cartesian co-ordinates and all points in the third quadrant have negative co-ordinates. More will be said about the choice of axes in Chapter 2. When the librations of the west or north limbs are favourable, the Moon is said to have a *positive* libration. Similarly, when the south or east limb regions are most exposed to the view of a terrestrial observer, the apparent libration is said to be *negative*.

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CHAPTER 2

Height Determination of Points on the Moon's Surface

2-1. The determination of relative heights

On the Earth, the heights of points are measured above sea-level. There is no such convenient datum surface on the Moon, and to compare the "absolute" heights of two widely separated lunar peaks, it is necessary to measure the altitude of each peak above the centre of the Moon. A stricter approach to this problem will be outlined below (2-4); for the present, only the measurement of "relative" heights will be discussed, in which the height is given of one specified point above another. Several methods are available for measuring relative heights.

The **Mountain Peak or Light Tangent Method** lacks accuracy but is of interest. The observer must note the time at which the illuminated peak of a mountain just within the dark hemisphere of the Moon either ceases to be visible (at sunset) or first becomes visible* (at sunrise). At the same time he must measure the angle subtended at his eye by the shortest line joining the mountain peak to the terminator (the boundary between night and day hemispheres of the Moon).

The method is very crude since the contrast between night and day fringes is always small and a sharply defined terminator is never seen. Furthermore, the time at which the mountain top is estimated to appear or disappear is a function of many things, such as the aperture of the telescope, and the observer's visual acuity.

By far the most useful and the most frequently used method is the **Mountain-shadow Method,** which involves measuring the angular length of a shadow cast by any peak of known position, at a given time. In this case, the height of the mountain, h, in units of the Moon's radius, measured above a spherical surface passing through

* This is not usually practicable.

the tip of the shadow and having the same radius as the Moon is given by

$$h = \frac{\cos(A - \psi)}{\cos A} - 1, \qquad (2\text{-}1\text{-}1)$$

where $$\sin\psi = \frac{r.s.\cos A}{5620'' \sin\phi} \qquad (2\text{-}1\text{-}2)$$

and the symbols have the following meanings:

A – the altitude* of the Sun at the position of the lunar mountain in question.

r – the distance between the observer and the lunar mountain, measured in terms of the Earth's equatorial radius.

s – the apparent length of the shadow cast by the mountain, measured in seconds of arc.

ϕ – the phase-angle†

A fairly complete analysis of this method may be found, together with a model solution, in a paper by MacDonald (1931c).

In 1937 a very sensitive method of measuring the irregularities of parts of the lunar surface was developed by McMath, Petrie, and Sawyer (1937). The method is basically the same as the one just described, but is more refined (see 2-3) and has a promising future: some results which have been obtained using McMath's method will be recorded below (2-3).

Results obtained from the Mountain-shadow Method, like those obtained from all other methods of estimating altitudes, contain errors. Discussions of these errors will be found elsewhere (1959a; 1959b; 1960a), but it will be noted here that one of the biggest sources of error lies in the fact that the positions of mountain peaks on the Moon are not known with sufficient accuracy. Total estimated errors may be as large as 10% of the altitude-difference in question but, under favourable conditions, this figure may become much smaller.

Even though of great accuracy as compared with other methods, the Mountain-shadow Method necessarily fails in extensive areas devoid of mountains. In such cases it is possible to measure relative altitudes by the use of a **Photometric Method.**

* The angle between the line joining the centre of the Sun's disk to the point in question, and the normal projection of this line on the tangent plane at that point.

† The angle between the lines joining the centres of the Moon and the Sun, and the centres of the Moon and Earth.

If a photographic negative of the Moon is scanned with a photometer across a gently undulating sunlit area (such as one finds in the maria), and in a direction parallel to the "brightness equator", then the land-profile corresponding to that scan may be ascertained. By making auxiliary scans in closely adjacent regions where there are no very obvious mounds or ridges, one may determine the mean, smoothed curve of transparency plotted against distance across the surface. By superimposing such a smooth curve, κ, on an individual photometric trace, τ, a point may be found on the curve κ which has the same intensity as any chosen point lying on the curve τ. The distance which separates the two points (measured parallel to the distance-scale) subtends at the centre of the Moon an angle numerically equal to the slope of the ground (measured from the local horizontal) at the point in question on the trace τ. A land-profile may be constructed by evaluating the slopes at a sequence of points on this trace.

Of course, it has been assumed that the ground is of uniform albedo. The albedos of the surface materials contribute little to the observed brightness if regions close to the terminator are under investigation; however, when close to the terminator, low swellings themselves may cast shadows which can interfere with the analysis, and tests seem to indicate that, whilst the method is very sensitive, it is not as accurate as the Mountain-shadow Method.

The Photometric Method appears to have been applied to the Moon for the first time by van Diggelen (1951), who used it to make a contour map of a small part of Mare Imbrium close to Pico, and to obtain land-profiles of wrinkle-ridges in the south of Mare Imbrium (see 2-3).

The **Comparative Method** applies to two mountains placed at approximately the same latitude, and so situated that they cross the terminator at nearly the same time. If each mountain is casting a shadow, and if the height of one of the mountains is known, then the approximate height of the other may be found by simple proportion by measuring the lengths of both shadows.

Relative heights may also be estimated by making **Direct Measurements At or Near the Limb**.

Quite apart from the measurements of heights of limb mountains it is important to know the limb profile in order to see how much the irregularities might affect the times of disappearance and reappearance

of occulted stars. That there are differences in the Moon's position at a given time as derived from occultations, on the one hand, and meridian observations on the other, has been noted by Brown (1933), who quotes his sources. Such differences would be attributed to the irregularities of the profile, inaccurate star-positions,* and changes in the rate of rotation of the Earth.

Apparent relative heights may be obtained by direct measurements at the telescope or on photographs. It would not generally be possible to give altitudes of such limb mountains above their bases, except as rough approximations.

A modification of this method may be applied to mountains which are not in the plane of the limb, but which are not far removed from the limb, being displaced from it in the direction of the centre of the visible surface. The inner walls of many craters situated near to the limb are particularly well suited to this method, as the bases of such mountains are usually fairly well defined due to the generally smaller brightnesses of the crater floors. However, one must assume the value of the slope of the wall in question. Great accuracy cannot be achieved by this method.

In the first attempt to compile a comprehensive atlas of lunar profiles, Weimer (1952a) produced seventy-two charts of the east limb profiles, and a further seventy-two charts of the west limb. As raw material, he used a selection from between 2000 and 3000 of the plates of Loewy's and Puiseux's which were made between 1894 and 1909; more recent plates were not sufficiently numerous or did not record all librational positions; the object was to find the profiles for all different librations and parallaxes, since the limb profile varies with all these quantities.

As an example of such variations, Weimer (1950b) has given three traces made over the same position angles on plates taken at different times. The first was taken on 10 December 1894 ($l = -5°{\cdot}972$, $b = -4°{\cdot}913$),† the second on 11 December 1894, and the third on 4 March 1895 ($l = -7°{\cdot}164$, $b = -6°{\cdot}433$). Small differences between the first two profiles indicated errors of measurement. However, whilst the third result showed the same *general* form, in detail this profile was quite different from the previous two. The changes could not be attributed to errors of measurement.

* Meridian observations are referred to observations of standard stars.

† l = total libration in longitude, b = total libration in latitude (degrees selenocentric).

In Weimer's finished atlas, the heights have been plotted in geocentric seconds of arc, for the *mean* Earth–Moon distance, against the position angles as abscissae. (Position angles are measured from the line joining the Moon's centre to its north pole and are positive proceeding southwards through east. Weimer defined his position angles by means of craters of well-known co-ordinates.)

In a later publication, Weimer (1954e)* has discussed in detail his methods of obtaining these profiles. The optical tracing method of the *camera lucida*† was found to be the best of the three methods which he examined. In this method a given plate was made to revolve in its own plane about an axis normal to it and passing through the centre of the Moon's disk. By optico-mechanical action, records were drawn upon a paper tape which moved 5 mm when the plate turned 1°.

In the **Eclipse Method**, photographic observations are made of the curve of contact of the two bodies when the Sun is eclipsed by the Moon.

Whitwell (1929b) has given a section in a plane through the centre of the Moon and normal to the line of sight, with relative heights scaled up thirty-five times. He found that the maximum angular difference between the lowest and the highest part of a limb irregularity was 4 sec of arc geocentric‡: for a star incident normally to the limb, this would yield an occultation time $T = t \pm 4{\cdot}5$ sec where t is the predicted occultation time, and the time variations might possibly be even greater for oblique incidences. However, as Whitwell has pointed out, the observed variations would in general be only fractions of these times, because the limb would usually be relatively smoother, due to background and foreground mountains.

A simple eclipse method of investigating the coarser features of the profile has been described by Fujinami (1952b). Using cine-film, he took pictures at intervals of $0^s{\cdot}04$ with a telescope of focal length only 1·4 m. Times were printed on the sound track of the film. At a given time, it was necessary to measure the angle θ between the line drawn parallel to the direction of the Sun's motion through the centre of the disk of the Moon, and the line joining this centre to a point of contact of the Sun and the Moon (both bodies being considered to be disks in the plane of the sky.) Fujinami compared his results (h plotted against θ) with those of Hayn (1906; 1909; 1914) and found that the dimensions h of the limb mountains and valleys

* (A condensed account was given earlier, by Weimer, 1950b.)

† A piece of apparatus in which the image of an object is reflected on to a screen.

‡ A value which was confirmed later by Fujinami (see below).

were generally larger—and occasionally much larger—than those found by Hayn. Hayn's limb profiles were made up from measurements which were corrected for the phenomenon of irradiation, but the scatter of the points was large and smooth curves were drawn through them. Thus, the curves could not pretend to include any detailed structure.

Further work was done by Fujinami, Ina and Kawai (1954b) on the partial eclipse of 1953, 14 February. They used a Cooke photovisual refractor of aperture 30 cm and focal length 4·55 m, to photograph the silhouetted lunar profile. An orange filter of large absorption was placed in front of the photographic plate: this combination gave a passband of 480–510 μ and, with the objective diaphragmed to a diameter of 10 cm, the exposure time was about 1/15 sec. In this paper, a profile of 140° of the limb is given in diagrammatic form. The limb is shown to be much more jagged, and the height-differences much greater than are shown in Hayn's (1914) curves. The largest height-difference was found to be of a peak contained by the Leibnitz Mountains. This had a value of 4″ arc geocentric, and from the diagram it would appear that height-differences of 3″ arc were common.

In the **Occultation Method**, observations by photo-electric means of the occultation curves of stars of large angular diameter allow the diameters of the stars and the slopes of the limb irregularities to be estimated. It has been pointed out by Evans (1955b) that if two observers, separated in terrestrial latitude by, say, 20° (but not necessarily being very close in terrestrial longitude), recorded the occultation curves of the same star, it might be possible to measure two nearly orthogonal diameters of the star. Evans has given the occultation curves of some stars of large angular diameter: these take a general characteristic form, but the curves are liable to distortion due to the limb irregularities. It is possible to compute the curves for various models and compare these with the observed curves. The forms of the limb irregularities may be examined in this manner. Another method of estimating slopes of limb formations, utilizing the phenomenon of diffraction will be mentioned below (2-2).

By virtue of the fact that the Moon suffers librations, it is possible to photograph it at times so spaced that the effects are the same as those which would have been realized had the photographer himself moved along a "base line" and had the Moon remained stationary.

The principles of the **Photogrammetric Method** are described in any textbook on the subject, such as Trorey's (1950a). It is obvious that the sensitivity of the method, when applied to the Moon, must be very small if the base line is small. Hence, it is important to select photographs which depict extreme librations.

Suppose that the resultant of the total librations in latitude and longitude is represented by a libration of θ degrees. One of the standard photogrammetric formulae which may be used to estimate the height h of a lunar formation is

$$h = \frac{H^2.\delta p}{b.f}\,, \tag{2-1-3}$$

where H is the distance between the Earth and the Moon at the time when the photographs were taken, b is the average absolute photobase (which may be found from scaled-up measurements on each photograph), δp is the measured difference in parallax, and f is the *equivalent* focal length of the camera (telescope) which was used to take the photographs. (This value of f includes any changes incurred by using enlargements. Such enlargements would have no advantage over contact prints as long as the grain in the contact prints could just be detected with the usual (×6, say) magnification of the photogrammeter's binocular attachment.) Since $b = H\theta$, equation (3-1-3) may be written

$$h = \frac{H.\delta p}{\theta.f}\,. \tag{2-1-4}$$

Considering favourable circumstances, in which $H =$ 370,000 km for each photograph (the mean distance of the Moon being 384,400 km), $\delta p = 0{\cdot}005$ cm (measurements of greater precision being limited by grain-size and other factors), $\theta = 10°$, and $f =$ 4000 cm (for a prime-focus contact picture taken with a telescope like the 100-inch reflector at Mount Wilson), it is seen from equation (2-1-4) that $h = 2{\cdot}6$ km. This means that, under the circumstances stipulated, differences in altitudes of this order could just be detected and small differences would be very uncertain. In the latter case, averages of many measurements would reduce the probable errors.

It is seen from this analysis that it should be possible to measure differences in altitude of the order of 2–3 km. In principle, this is the method used for estimating the figure of the Moon.

The earliest stereoscope used for these purposes seems to have been Schwassman's (1902). Klein (1903a) has described how Pulfrich applied this instrument to the Moon. Using Lick Observatory photographs, Pulfrich confirmed "to a certain extent" Franz' measurements of altitudes. Klein pointed out that the photogrammetric method has an advantage in that one can measure the altitudes of flat regions just as well as one can measure the altitudes of distinct points in the highlands. The resolvability in height which Klein gave (200–300 metres) would seem to be highly optimistic. He said that Pulfrich succeeded in measuring the heights of walls above crater bottoms, but no results were given. Doubt is thrown on the method of reduction employed because, with a large stereobase (corresponding to a total libration change of 14°) the Moon was found to be egg-shaped, and the Moon became more spherical as the base line decreased. Nevertheless, the attempt to apply this method is of historic interest.

In 1930, a project of mapping 100-ft contour vertical intervals by stereoscopy was started by the Moon Committee of the Carnegie Institution, according to Wright (1930). No results have been published, and it would seem from what has gone above that the proposal to map with such a small vertical interval was rather optimistic.

Finally, relative heights may be determined **From Absolute Heights**. Given the absolute altitudes of any two points it follows that their relative heights can be obtained by subtraction. This is essentially the method used in obtaining the figure of the Moon. The method of obtaining absolute heights will be considered below (2-4).

2-2. The determination of slopes

If the Moon were a perfect sphere, the form of the terminator would be an ellipse varying in eccentricity from zero to unity. Deviations from this perfect curve indicate deviations from the spherical form. Fauth (1907) has said that Mare Imbrium rises in a gradual incline to the feet of the Apennines: presumably he used this qualitative method, for it is easy to confirm, by examining the shape of the terminator, that Mare Imbrium does appear to rise up towards the Apennines. The increase in level must be appreciable, since the terminator here is not far from the central meridian. This method becomes more sensitive as the eccentricity of the terminator decreases: it is particularly useful when searching for domes, or for seeing whether or not craters lie on domes. Slopes in maria are always extremely small (if occasional mountain-peaks and craters are neglected). Even the wrinkled parts rarely have slopes exceeding 2°, and the slopes of dome-like swellings are also of this order of magnitude.

Unlike the inner walls of large craters, outer walls generally have no clear boundary at their lower ends. This, together with the fact

that their slopes slowly become vanishingly small on proceeding away from a crater, means that the slopes of outer walls of craters are not easy to determine precisely. A very rough indirect method has been given by MacDonald (1931b), from a formulation of Schroeter's Rule. *Schroeter's Rule* states that the volume of the materials forming those portions of the ringwalls of a crater above the mean surface level at the place in question is, in general, approximately equal to the volume of the craterial depression measured below that mean surface. It is obvious that a very great amount of time and labour was spent in observation and in computation, before this important rule was formulated. MacDonald suggested that the rule might be explained by isostacy. In MacDonald's method, only average slopes are considered, and the truth of Schroeter's Rule is assumed, which means that slopes determined in this way could scarcely be more precise than those determined from shadow observations, since Schroeter's Rule was derived from such observations. The formula which MacDonald gave for the outer slopes of crater-walls was $\cot^{-1}(7\Delta^{\frac{1}{2}})$ where Δ was the diameter of a crater.

Fauth (1907) deduced that the average slopes of the outer walls of craters lay between 3° and 8°, and measured many inner slopes at broadly-grouped altitudes. Fauth's (1895) mean inner slopes have been compared with Schmidt's slopes by MacDonald (1932a), who tabulated these estimates with crater-diameter groupings. MacDonald found reasons to separate craters with and without central peaks, from a study of the slopes of 184 objects the slopes of which had been estimated by Schmidt (see Table 2-2-1).

MacDonald argued that Schmidt's values were maxima, while Fauth's were mean values, and hence explained the apparently large discrepancies between the two observers. This explanation would seem to be very reasonable in view of the fact that agreement is closer as the size of the crater diminishes; the observers would not have found it possible to measure anything but the average slopes of the smallest craters. That Schmidt's values clustered around angles of 30° indicated, according to MacDonald, that erosion had produced a state of equilibrium. Table 2-2-1 can readily be interpreted in terms of Gold's (1955c) dust theory.

Wright (1935b) has described the work of the Carnegie Institution Moon Committee, which used cinephotography for slope determinations of crater walls, and thus determined the times of appearance or

TABLE 2-2-1

Diameter range (km)	Objects with cent. peaks (°)	Objects without cent. peaks (°)	Fauth's means (°)
135–200	30·0	26·4	11·6
100–134	31·0	27·5	
80–99	30·5	27·1	14·8
60–79	29·4	28·2	
50–59	32·7	28·8	
40–49	32·9	30·7	22·7
30–39	36·4	36·6	
20–29	35·6	34·9	33·5
10–19	37·9	35·3	

disappearance of shadows. The solar altitudes, computed for the times and positions in question, correspond to the slopes of the crater walls. The inner walls of small craters were confirmed to be steeper than those of large craters. Later, Wright (1938) wrote, "On small craters, a mile or two in diameter, the angle of the inner slopes may reach 55°; this angle is surprisingly large if the materials are of the nature of volcanic ashes and pumice."

Delmotte (1939) has given a simple graphical method of finding inner slopes, and found values of 30–40° for the steeper parts, clustering around 35°. MacDonald (1940) mentioned this paper, and noted that H. D'Halluin had previously obtained smaller angles ($\sim 20°$) "presumably for the average slope". Maintaining that the angle of stability of a lunar scree slope would be 30°, after crumbling due to temperature changes,* MacDonald said, "... one would therefore expect the slopes to be slightly larger than that figure, as further crumbling and slipping must be very slow when the process is approaching stability". This would not apply, of course, to slopes which were originally less than 30° in value.

* Presumably, MacDonald (1931b) had observed that the critical angle of slope was "close to the maximum angle of stability of a terrestrial scree slope".

The slopes of fault-faces have not been measured accurately. The Straight Wall—the best-known fault on the face of the Moon—has been depicted as a vertical cliff, whereas in reality the slope does not seem to exceed 44° from the horizontal (Ashbrook, 1960c).

Slopes of limb mountains may be measured either directly at the telescope or from photographs, or indirectly by Evans' occultation method. A description of this method applied to stars of large angular diameter has been given above (2-1). For stars of negligibly small angular diameter, Evans (1955b) has used another method for finding the slopes. This makes use of the fact that the spacing in time of the oscillations in brightness of the diffraction pattern of the star is affected by the average slope of the rough regions behind which the occultation occurs. Average slopes ranging from 1° to 18° have so far been found by this method. If these are slopes of crater walls, and not of isolated mountains, then their small values are readily understandable: they must apply to the outer walls of craters. Evans has pointed out that if slopes are found to be commonly greater than 20°, errors in the star-diameters deduced by the occultation method will be frequent.

A special case for stars of large angular diameters arises when a star is occulted twice at the same limb. It would be possible to estimate three separate slopes in this way. The phenomenon—or one giving similar effect—has been observed visually on many occasions.*

Evans has written, "If slopes of angle $\theta°$ occur, double disappearances at occultations at angles of incidence greater than $(90 - \theta)°$ are possible. If the eye can be reckoned capable of seeing a reappearance lasting 0·1 sec, visual observation should be capable of discovering slopes of the order of $0''{\cdot}04$ in length and only a fraction of this in height. Photoelectric observation should be capable of detecting slopes very much smaller than this. The Cape Observatory now has about forty photoelectric observations of occultations, none of which shows this phenomenon. It is understood that double disappearances have been observed visually only at grazing occultations."

In contrast to this last suggestion, Firsoff (1956a) has observed intensity fluctuations of stars one of which was occulted at far from grazing incidence. He was observing in blue light, and proposed an entirely different explanation of the intensity fluctuations—namely,

* See Evans (1955b); Firsoff (1956a).

that they were affected by a tenuous lunar atmosphere. It seems more probable that the observed fluctuations were due to conditions in the Earth's atmosphere.

Finally, it should be mentioned that slopes may be evaluated from measured land profiles (cf., eg., Fig. 2-3-7) and, in maria, by photometric studies: (2-1).

2-3. Lunar formations in profile

Many measurements made by Schroeter (1791; 1802) and Schmidt have been listed together with their own measurements in a table of 1095 mountain heights by Beer and Mädler (1873).

The early selenographers certainly appreciated the fact that the lunar craters were relatively shallow formations. Goodacre (1926) has drawn some east-west sections of craters roughly to scale, using the figures of Neison (1876) "who has largely adopted the results of Mädler and Schmidt" (see Fig. 2-3-1). The sketches, modified for

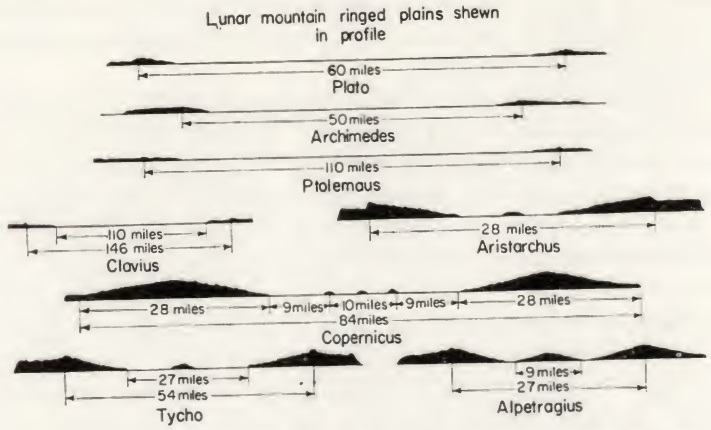

FIG. 2-3-1. Crater profiles: Goodacre (1926). (*Journal of The British Astronomical Association*)

curvature, show very well the general shapes of the larger craters. Similar sections, not modified for curvature, have been given, recently, by Alter (1956b), and it is interesting to note that Alter shows (Fig. 2-3-2) no outer slopes of the walled planes, whereas Goodacre does show outer slopes.

Blackhall (1929a) analysed the heights given by Neison, and found that the eastern ramparts of craters in the western hemisphere were

generally higher than the western ramparts, and that, in the eastern hemisphere, the western ramparts of craters were generally higher than the eastern ramparts. Thus, the apparently higher (eastern or western) ramparts of a given crater were in general those further from the nearer (east or west) limb. It would seem that there was a source of systematic error in the method of the measurements.

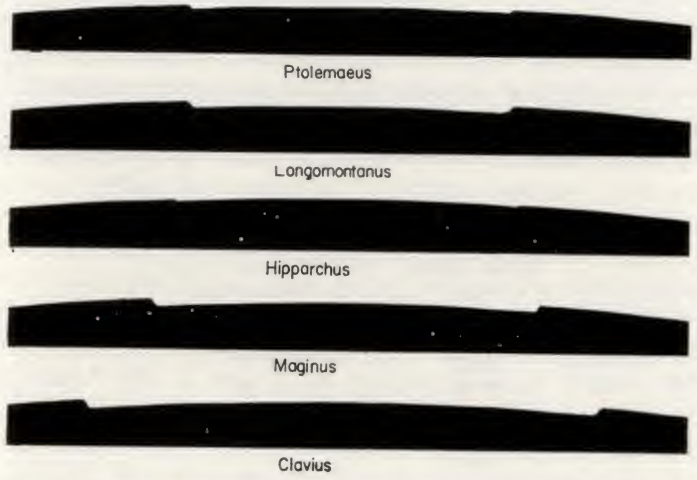

FIG. 2-3-2. Crater profiles: Alter (1956). (*Publications of the Astro. Soc. Pacific*)

Starting in 1929, MacDonald (1929c) produced a series of very useful papers on lunar statistical problems. To a certain extent this first paper supported Blackhall's results, yet it also indicated that the differences in the altitudes of the east and the west walls of craters were not always of similar sign for a given hemisphere: craters with their west walls higher than their east walls tended to cluster together, as did those with east walls higher than their west walls. For this analysis, MacDonald used Schmidt's data, and he has given a rough map showing the point on each of many crater walls at which the relative altitude is a maximum. A table of heights of walls above both insides and outsides of craters was also given.

Ebert found that the ratios of the depths of craters δ (measured from the tops of their ringwalls) to their diameters, Δ (measured between ringwall-tops) decreased with increasing diameter. This relationship became known as *Ebert's Rule.*

Over 400 relative altitudes of peaks and crater-walls, in the Moon's northern hemisphere, were measured by Schrutka-Rechtenstamm (1954a), who used three sunrise and three sunset plates of the Paris Atlas supplemented by five sets of sunrise and five sets of sunset micrometer measurements at a 27-inch refractor. A rough, quantitative demonstration of Ebert's Rule, based on Schrutka-Rechtenstamm's depth-measurements, is provided in Table 2-3-1. The diameters of the craters were taken from the I.A.U. list, and since this list quotes diameters only to the nearest thousandth of a lunar radius, lower limits of the ratios δ/Δ have been given in Table 2-3-1, by dividing the mean estimated depth by the maximum permissible diameter, in each case. Using mainly the weighted means of Schmidt's

TABLE 2-3-1

Diam. group (km)	Approx. ratio δ/Δ (%) (lower limits)
5–15	12*
20–30	9
35–50	6
50–70	5
70–100	3
>100	<3

* Possibly this figure should be increased; see below.

data, MacDonald (1931a) plotted the depths δ (in km) against the diameters Δ (km) of many craters with central mountains and found that the relationship which evolved, $\delta = 0{\cdot}378\Delta^{\frac{1}{2}}$ was a means of predicting the ratios given by Ebert. MacDonald found that the continental craters around Tycho had larger δ/Δ ratios than other craters, giving $\delta = 0{\cdot}378\Delta^{\frac{1}{2}} + 0{\cdot}95$. In his next paper, MacDonald (1931b) treated walled planes (defined here as craters having no central mountains), and found $\delta = 0{\cdot}234\Delta^{\frac{1}{2}}$. He pointed out that if the walled planes were flooded craters, then the relationship $\delta = 0{\cdot}378\Delta^{\frac{1}{2}} - c$ would hold for them, where c would be a positive constant if the flooding had been uniform, or would vary irregularly if the flooding had been accidental. In fact, he found that c was a function of the diameter-grouping and concluded "Such flooding appears difficult to account for". It does not seem impossible,

however, that some erosional theory, such as Gold's (1955c) dust theory, in which the rocks forming the lunar slopes are continually being eroded by the action of ultra-violet light from the Sun to form a very fine dust, could explain the observed variation of c. Plotting the heights of ringwalls measured above the external planes of craters and of walled planes, against their diameters, MacDonald found $\delta_0 = 0{\cdot}153\Delta^{\frac{1}{2}}$ for both types of formation.

Among other results, Hopmann and Behrmann have given the mean depth of a set of craters of mean diameter 15 km, as 2·23 km. The mean external wall height for this grouping they gave as 0·45 km. The first result gives a depth:diameter ratio of 15% (cf. Table 2-3-1), which is in good agreement with the results of Fielder, Moore, and Warner (1960a) for craters of 10–20 km diameters. To secure sections of lunar landscapes in the north–south direction is not easy. There are several obvious selenological faults which are inclined but little to this direction, yet there are no obvious ones which run from east to west. One possible fault of the latter class runs from the crater which lies in the south-east wall of Cichus, eastwards towards Capuanus. This is not at all certain, however. Neate (1935a; 1936a; 1958a), who used visual and photographic observations of the sunrise shadows of the eastern walls of Cichus, deduced that the land dropped by about the order of 350 m to the south of the line, but he thought that the effect might have been produced by a ridge.

A rough section of the crater Ptolemaeus A was given by Neate (1936b) from measurements on Yerkes, Mt. Wilson, and Paris photographs. The section is not reproduced here, but a warning against connecting a very few measured points by a smooth curve is given by comparison of this section with that of the same crater deduced by Neate (1954c) eighteen years later after more photographs had become available and more visual observations of the crater had been made (see Fig. 2-3-3a); and, again, with the author's (1960b) profile of Ptolemaeus A (Fig. 2-3-3b).

Using a modification of the Mountain-shadow Method (2-1) McMath, Petrie, and Sawyer (1937) were able to plot small differences in the altitudes of the ground over which a shadow-tip had travelled in a given time. These differences in altitude—smaller than any which had been measured previously—could be referred to a point of standard altitude. A description of the apparatus used has been given by McMath, Hulbert, and McMath (1932b). Cine

photographs were taken at intervals of about ½ min, with a 10½-in. Cassegrainian reflector.

By this method, the authors (1937) secured sections of restricted parts of the floor of Theophilus (see Fig. 2-3-4), with a sensitivity

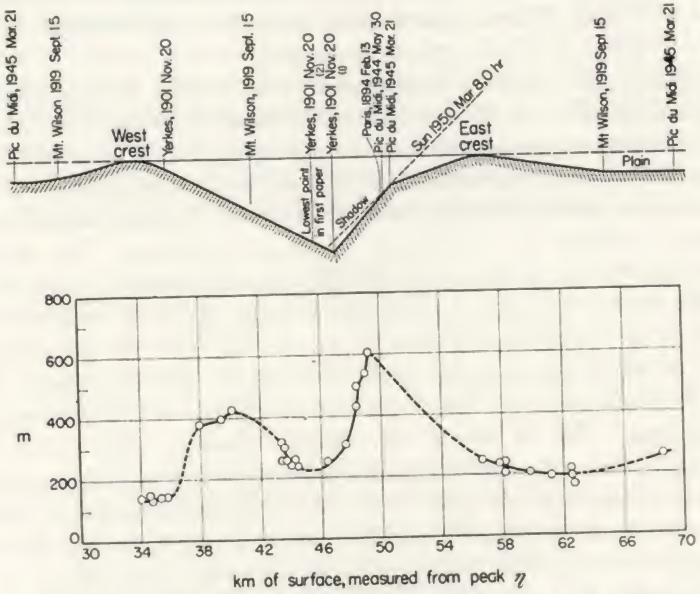

FIG. 2-3-3. Profiles of Ptolemaeus A: (a) Neate (1954); (b) Fielder (1960). ((a): *Journal of The British Astronomical Association*; (b): part of the work which led to this profile was done under the support of the *Geophysics Research Directorate of the U.S. Air Force Camb. (Mass.) Research Centre*)

which surpassed that of all previous work, and they deduced an approximate section of the whole crater (see Fig. 2-3-5).

An explanation of the sometimes widely differing estimates of relative altitudes was furnished by these results: for the highest central peak in Theophilus, for instance, individual measurements could yield relative heights above the crater floor varying from about 1920 m to 2650 m.

Cross (1954d; 1955a) has devised a neat method of deducing the general shapes of the smaller lunar craters which appear to be bowl-shaped. The craters examined in this way must be perfect in that their ringwall-tops must be circular and must lie in horizontal planes.

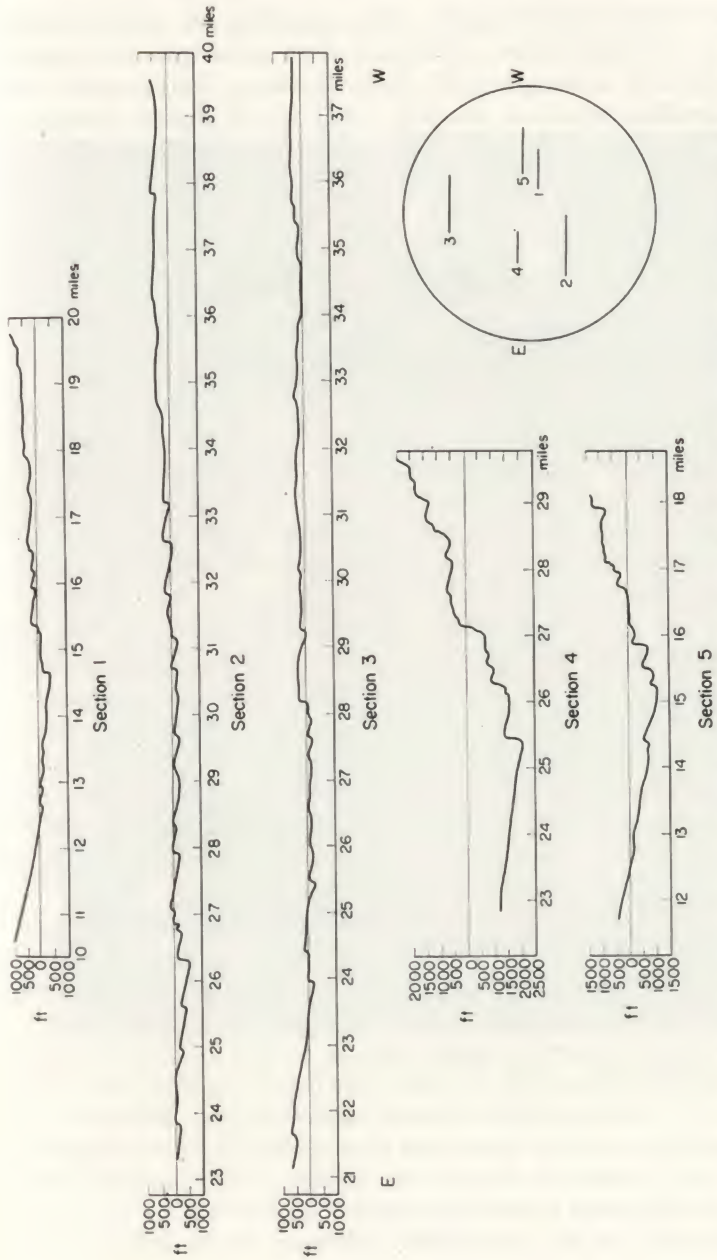

FIG. 2-3-4. Profiles of different parts of the floor of Theophilus: McMath, Petrie and Sawyer (1937). Vertical scale = 2·2 × horizontal scale. The general shapes of the curves are of interest, but the small irregularities shown cannot be real. (McMath-Hulbert Observatory of the Univ. of Michigan, Pontiac (Mich.))

Cross showed mathematically that regarding the shadow-form within a conoidal crater, a change in the vertical scale was simply equivalent to a change in the Sun's elevation. Furthermore, the orthographic projection (see Fig. 1-2-1) of the shadow boundary

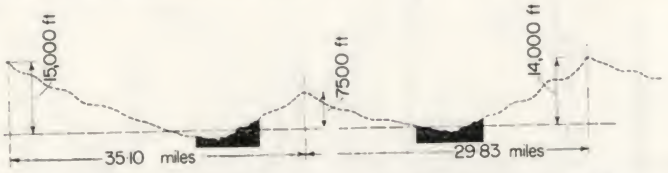

FIG. 2-3-5. Profile of Theophilus, along an east-west diameter: McMath, Petrie and Sawyer (1937): (McMath-Hulbert Observatory of the Univ. of Michigan, Pontiac (Mich.))

within paraboloidal craters was the arc of a circle of radius equal to that of the crater. He proceeded to show, simply from an examination of the geometry of the shadows inside the craters that, of 117 small craters placed near to the centre of the Moon's disk, 52% approximated to the paraboloidal shape, 26% were ellipsoidal, and 10% were probably hyperboloidal.

Working at the Pic-du-Midi Observatory, the author applied the method of McMath and his colleagues, mentioned above, to the task of measuring the cross-section of a wrinkle-ridge—a name given to the winding ridges which are found on the Moon and resemble wrinkles. A picture of the neck which connects Mare Imbrium with Mare Serenitatis has been printed in Fig. 2-3-6. In it will be seen a mountain peak, designated β by Wesley and Blagg (1935), and casting a tapering sunrise-shadow to the east (right) in the direction of a prominent wrinkle-ridge which has been indicated by arrows. Pictures were taken once a minute, and for as long as the shadow-tip of peak β was crossing the ridge. Measurements of the different lengths of the shadow of this mountain at different times enabled a profile of the wrinkle-ridge to be constructed (Fig. 2-3-7a).

The ridge is seen to be complex; the top is not of uniform curvature and is of the order of 200 m higher than the surrounding land. The profile of another wrinkle-ridge in Mare Imbrium, north-east of Eratosthenes, has been determined photometrically by van Diggelen (1951) and is shown in Fig. 2-3-7b. Baldwin (1949) suggested that wrinkle-ridges were ancient flow-marks. If this were the case, one would expect to find appreciable differences in the levels of the

FIG. 2-3-6. The " neck " joining Mare Imbrium and Mare Serenitatis. The wrinkle ridge mentioned in the text is indicated by the arrows. The shadow of peak β crosses over it

country to either side of a wrinkle-ridge. The author has been unable to find decisive evidence for the general existence of such differences. Visual examination of other large wrinkle-ridges, under excellent conditions, has shown that there may be two or more parallel crests, like minor mountain chains lying on top of a broad, mountainous base.

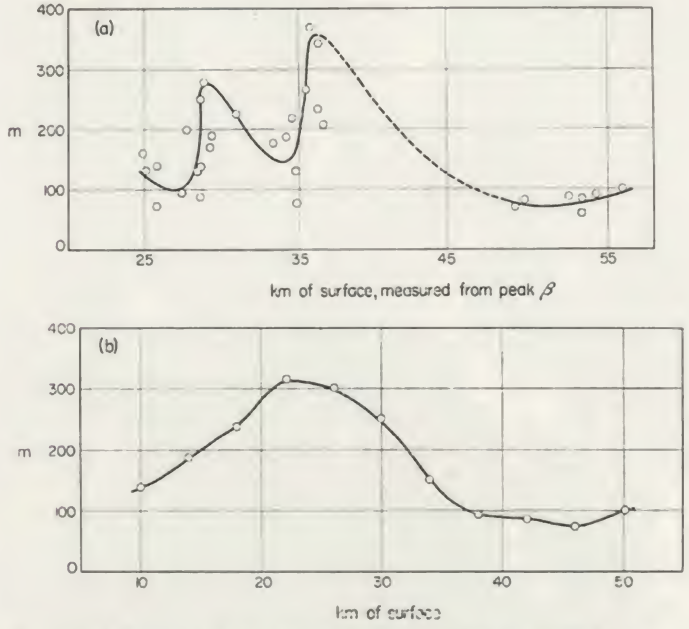

FIG. 2-3-7. Profiles of two wrinkle ridges: (a) Fielder (1959); (b) van Diggelen (1951). Fielder's profile was determined by shadow measurements; van Diggelen's was determined photometrically

2-4. The determination of Absolute Heights

The method of measuring absolute heights of points—that is, the distances between points exposed on the surface and the centre of the mean sphere of the Moon—reduces essentially to the accurate measurement of the positions of these points. The principles involved in the measurement of positions are as follows.

It is first necessary to choose M, the centre of the mean sphere of the Moon, as origin of rectangular co-ordinates. It is customary to let the radius of the mean sphere be of unit length. The z-axis may be defined as that line which joins M to the centre of the disk which is visible at any instant, the positive direction being towards the

observer. The x- and y-axes then lie in the plane of the limb, with their positive directions westwards and northwards, respectively Suppose that it is possible to measure the true co-ordinates (xyz) of any point J on the Moon's surface (but not necessarily lying on the mean sphere); these will be known as the *instantaneous* co-ordinates of J at the time of measurement.

Consider now the very special case when the Moon presents its mean face to the observer—that is, when the Moon is in the position of mean libration. A new set of axes may be taken such that the ζ-axis joins the centre of the mean disk to the point M, and such that the axes in the plane of the mean limb are ξ (positive westwards) and η (positive northwards). Then $(\xi\eta\zeta)$ are termed the *standard* co-ordinates of the point J. It is easy to transform standard co-ordinates into selenocentric polar co-ordinates:

$$1 + h = \sqrt{(\xi^2 + \eta^2 + \zeta^2)}; \qquad \tan\lambda = \frac{\xi}{\zeta}; \qquad \tan\beta = \frac{\eta}{\sqrt{(\xi^2 + \zeta^2)}}.$$

Here, h is the altitude of the point in question above the mean sphere, measured in units of the radius of that sphere, λ is the selenographical longitude of the point, measured westwards from the centre of the mean disk, and β the selenographical latitude, measured northwards from the same origin. The instantaneous axes will coincide with the standard axes only when the Moon occupies its mean librational position.

All measurements must obviously be referred to some fixed reference system, and it is convenient to take the above-defined standard axes as this fixed system. In general, a point $(x_1y_1z_1)$ is not the same as the point $(\xi_1\eta_1\zeta_1)$ and the essential problem is to find $(\xi\eta\zeta)$ given any point (xyz). It is possible to carry out reductions of this sort on a photograph of unknown date, and a graphical description of the method which he uses has been given by Arthur (1955d). Given the time of the observation, the librations in longitude, $l°$, and in latitude, $b°$, can be found from tables. It can easily be verified from a diagram that

$$\left.\begin{aligned} \xi &= x\cos l - y\sin l.\sin b + z\sin l.\cos b, \\ \eta &= y\cos b + z\sin b, \\ \zeta &= -x\sin l - y\cos l.\sin b + z\cos l.\cos b. \end{aligned}\right\} \qquad (2\text{-}4\text{-}1)$$

The quantity z cannot be measured directly at the telescope, or from a photograph: this co-ordinate must be derived from the other two, by the use of the equation of the mean sphere

$$x^2 + y^2 + z^2 = 1 \qquad (2\text{-}4\text{-}2)$$

(the radius of the Moon being unity). In fact, even x and y cannot be measured directly, because there are certain corrections to be applied. The first is the correction from a conical to an orthographic projection of the Moon, explained in Fig. 1-2-1. The second is the correction for differential refraction in the Earth's atmosphere, and there are corrections to be applied for change of origin and scale and for optical distortions.

The number of investigations has been rather limited. A list of 133 positions mostly measured by Lohrmann, Mädler, and Neison has been published by Neison (1876). Franz (1894) has given references to his earlier papers in *Astronomische Nachrichten* which tabulate the ephemerides of Mösting *A* from 3 September 1889, up to the end of 1890. Later, Franz (1901b) produced a catalogue of the selenographical latitudes and longitudes of 150 points, referred to nine points of which the standard co-ordinates had been obtained previously,* from measurements made on five transparencies of the Lick Observatories' 36-in. refractor. Since positions measured in this way are based upon the positions of a few "standard points", they are called "secondary" positions or points. Franz (1903b) completed his catalogue with the co-ordinates of a further 158 points near to the west limb. He used, this time, a new plate taken with the 80-cm Potsdam refractor. This was followed by the work of Saunder (1900; 1901a; 1905; 1911). The first part of Franz' catalogue has now been thoroughly revised by Schrutka-Rechtenstamm (1958b), who has quoted errors in each of the co-ordinates.

A catalogue of collected limb measurements was compiled by Hayn (1909). It is unusual in that the selenographical co-ordinates are given by means of position angles (measured eastwards from the north pole) and degrees from the great circle (which he unconventionally called an "artificial equator") defined by the meridian $\pm 90°$. From this catalogue, Hayn drew up a chart which showed the contours of the limb regions, as though the limb were always being viewed from above, to nearly $\pm 10°$ to each side of this "artificial equator".

Arthur (1953a; 1953b) has listed the secondary positions of 72 points in Mare Humorum, and 293 points in Oceanus Procellarum. These measurements were based on 12 standard points.

* The positions of these nine small craters, including Mösting *A*, were tabulated by Franz (1899).

2-5 Summary

Various methods of determining the heights of lunar eminences have been reviewed in (2-1). The most accurate results may be obtained by using the **Mountain-shadow Method**, but when this method cannot be applied, as in marial areas which lack mountains, the **Photometric Method** of van Diggelen may be used.

The inner walls of craters 10–20 km in diameter have slopes of up to 35°. Smaller craters may have larger slopes, and larger craters have smaller slopes than this. The slopes of the outer walls of craters are of the order of only a few degrees (2-2).

The ratio of the depth of a crater to its diameter is 0·02 or 0·03 for craters 100 km in diameter, and of the order of 0·1 for craters 10 km in diameter (2-3). The curvature of the floors of very large craters tend to approximate to the curvature of the Moon's mean surface. The interiors of well-formed small craters tend to be paraboloidal.

The principle of the method of determining the heights of points on the Moon's surface above the centre of the Mean sphere of the Moon has been discussed in (2-4).

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CHAPTER 3

The Figure of the Moon

3-1. Discovering the non-sphericity of the Moon

Given sufficient positional measurements of sufficient accuracy, and made at different times, one may investigate how much the Moon's earthwardly-directed face deviates from the spherical form. That it probably does so may be inferred from the fact that it is not in a state of free rotation: one might expect that a body such as the Moon, which exhibits a physical libration (see 1-2) would be non-spherical. For example, a bulge on the Moon rendering it non-spherical would be subject to the the attraction of the Earth and any rotation of the Moon taking the bulge further from the Earth would be opposed by the Earth's attraction on the bulge.

If the Moon is considered as a spheroid of semi-axes a and b, and if b is the radius of the limb, which may be considered circular, then the body-elongation—or simply the elongation—ε_z, which is purely a ratio, may be defined by the equation

$$\varepsilon_z = \frac{a - b}{b} .$$

The subscript z has been used because this elongation is measured along the z-axis of the Moon, as defined in (2-4).

According to Detaille and Fournier (1903c) the investigations of Hansen, Gussew, and Beck in the mid-nineteenth century gave elongations of $+0{\cdot}003$ to $+0{\cdot}007$ for the earthwardly-directed semi-axis.

Franz (1899b) made measurements of the positions of several small craters spread widely over the disk and got $\varepsilon_z = 0{\cdot}00114 \pm 0{\cdot}00390$ probable error.* Franz concluded, however, that the assumption that there existed a positive elongation was not necessary to explain this result. It is important to notice that the probable error was

* The *probable error* of a measured quantity is the quantity which deviates from the mean of a set of values by an amount which is just as likely to be exceeded as not.

greater than the value of the elongation, which may therefore not have existed at all. As an empirical rule one may say that if a measured quantity x has a probable error e, then the true value of the quantity lies between $x - 4e$ and $x + 4e$. In this case, therefore, this means that ε_z probably lies between $-0{\cdot}01$ and $+0{\cdot}02$. Included with Franz' paper is a coloured contour map of the Moon which, again, must be very inaccurate. Klein (1902a) has tabulated the positions and relative altitudes of 62 of Franz' points, and has given a reproduction of Franz' coloured contour map. Fournier (1903c) has also given a reproduction of the map. The map would seem to show that the lowest part of the surface was in Mare Imbrium, and the highest part in the southern continent. A more up-to-date version based, however, on only 150 points, has been drawn by Schrutka-Rechtenstamm and Hopmann (1958b) and is reproduced in Fig. 3-1-1. From a study of fifteen of Franz' Königsberg observations and from six of his own Breslau measurements, Mainka (1901b) deduced that $\varepsilon_z = 0{\cdot}004 \pm 0{\cdot}013$ probable error. This may be interpreted to mean that ε_z cannot be greater than 0·06.

An attempt to determine the Moon's figure by the use of stereometry* was made by Pulfrich and has been reported by Klein (1903b), but these measurements were not reliable, and are only of historic interest.

Pickering (1903a) selected twenty of Franz' (1901a) points (all small craters) which lay "within half a radius of the mean centre of the disk" and found that the average extra absolute height of the points situated in mountainous country with respect to the mean altitude of points on the limb was $3{\cdot}2 \pm 0{\cdot}8$ km and, for mare points, was $1{\cdot}3 \pm 1{\cdot}3$ km. Omitting Guericke C and Sinus Medii B, this latter result became $1{\cdot}1 \pm 0{\cdot}8$ km. To find his elongation of $0{\cdot}0013 \pm 0{\cdot}0012$, Pickering divided the average altitude of the twenty craters above this "mean" sphere by the radius of the Moon, which he took as 1740 km. (The presently accepted figure is 1738 km.)

From measurements of thirty-eight points, all situated near to the central meridian, Saunder (1905a) deduced for the elongation of this horst $0{\cdot}00052 \pm 0{\cdot}00027$ probable error. Nevertheless, Saunder stressed that the individual measurements were "subject to considerable uncertainty", and that the number of points employed was too

* According to Detaille and Fournier (1903c), Warren de la Rue applied *stereoscopy* to the Moon in 1867.

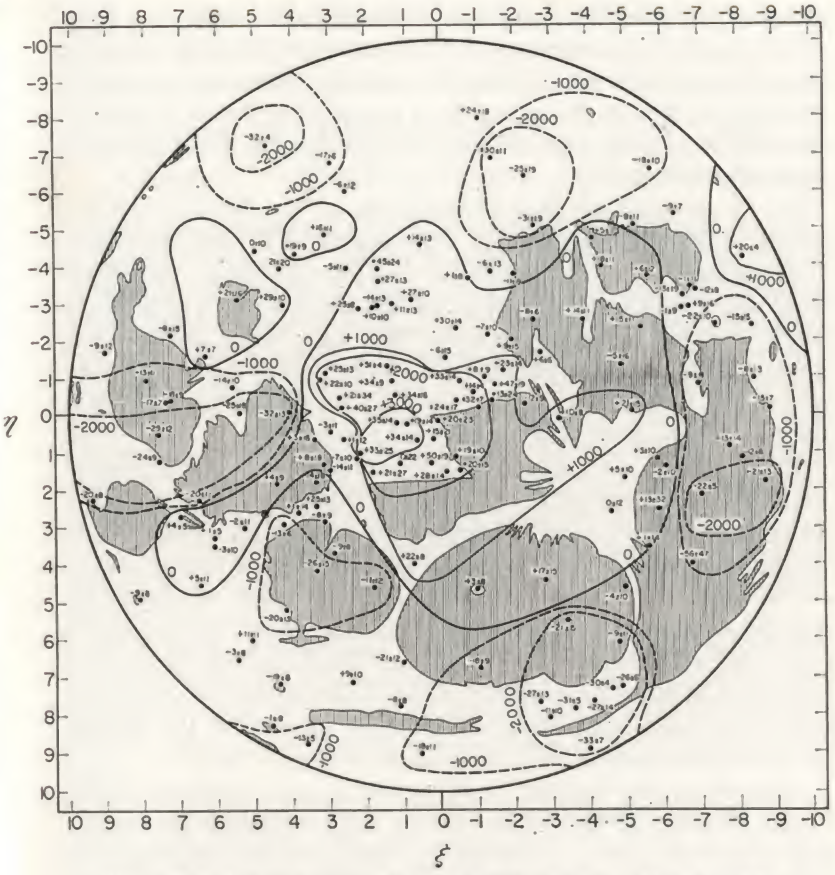

FIG. 3-1-1. Contour map, of the Moon's "near" side: Schrutka-Rechtenstamm and Hopmann (1958). This has been based on revised measurements of Franz. (*Sitzungsberichten der Österreichischen Akademie der Wissenschaften Mathem.-naturw. Klasse*, Abt. II)

small to allow any stress to be laid on the actual result, although the method was good. It happened that the largest radius of the Moon which he found was smaller than the radius of his mean sphere, which had been chosen to be of unit length. "The true explanation is . . ." wrote Saunder, "that the accidental irregularities of the surface are considerably greater than the elongation."

This is an important point which seems to have been overlooked by most theorists: with the true variations in absolute heights as they

are, it is obvious that the geometrical elongation must vary from point to point in a manner which cannot be predicted by assuming that these points lie on an ellipsoidal surface. Hence, the results of investigators who have used different groupings of points would not be expected to agree even within the limits dictated by the probable experimental errors.

As an example of this characteristic of the Moon's surface, Saunder (1905a) has shown that, if he omits from his data two points —Anaxagoras and Anaxagoras *A*—the deduced elongation (0·00123 $\pm$ 0·0029 probable error) of the Moon's prime meridian is larger than the previously deduced value by a factor of two. It is important to note that neither result demonstrates conclusively the presence of an elongation. The most that can be said safely is that if there is an elongation, then it does not exceed 0·01.

Hayn (1902b) concentrated on measurements of only one point—the small crater Mösting *A* which is near to the centre of the Moon's disk—and found the semi-axis joining the centre of the Moon to this crater to be 1·0023 units long, where the unit was the average radius of the limb. This gives a bulge of 4000 m. Hayn assumed that Mösting *A* was on the mean sphere: the assumption, he said, could not be proved. Weimer (1954a) said that Hayn's measurements were inaccurate because the diameter of the Moon on Hayn's plates was only some 3 cm. (The observations were made with the Leipzig 30 cm refractor, which has a focal length of only 3·596 m.)

Measuring some eighteen small craters in each quadrant of the Moon, Weimer (1948a; 1954a) found, after weighting the results, that all craters gave $\varepsilon_z = 0{\cdot}00335 \pm 0{\cdot}00027$, or that the bulge was of magnitude 5·8 $\pm$ 0·5 km. If the error quoted is a probable error, this positive result indicates that there may be an elongation of at least 3–4 km.

Taking yet a different approach, Baldwin (1949c) reduced the measured points of Franz and Saunder to the same system of units and tabulated the results. He plotted the deviation from the mean sphere against the orthogonally projected distance of each point from the centre of the disk for (a) continental points (points lying in the lunar "continents", which are the brighter, mountainous regions), and (b) points lying in maria (the darker areas, or "seas"). This rather obvious step of separating the continental- and the mare-points had been taken previously by Pickering (1903a), but Pickering had not

gone any further than this with his analysis, and Baldwin was able to show for the first time that the *tidal bulge was of the same magnitude in the continents as in the seas*. His results, with probable errors, are

$$\varepsilon_z \text{ (continents)} = 0{\cdot}00130 \pm 0{\cdot}00012 \qquad (2{\cdot}26 \pm 0{\cdot}21 \text{ km}),$$

$$\varepsilon_z \text{ (maria)} \qquad = 0{\cdot}00117 \pm 0{\cdot}00021 \qquad (2{\cdot}03 \pm 0{\cdot}37 \text{ km}).$$

Baldwin's analysis of points in accordance with their topographical positions yielded two interesting facts: firstly, the maria average 1740 m lower than the continents at the centre of the disk (Pickering 1903c found about 190 m) and 1520 m lower at the limbs. Secondly, to quote Baldwin, "the higher scatter of points on the lava flows* is due to real variations in surface level". The fact that the seas show level differences of greater magnitudes than in the continents has been confirmed recently by DuFresne (1956) who used modern statistical methods but, as the basis of his calculations, again used the measurements of Franz and, to a lesser extent, those of Saunder.

Murakami (1949b) has suggested an ingenious, if inaccurate, method of estimating the amount by which the Moon's earthwardly-directed axis exceeds the other axes.

If the craters are assumed to be circular all over the Moon's face, they will in general appear as ellipses on the disk, their minor axes directed towards the centre of the disk. Measurements of the lengths of these axes would provide measurements of the curvature of the Moon.

By assuming that any section of the Moon passing through its centre and containing the line of sight was an ellipse of semi-axes *a* and *b*, Murakami found from measurements of 327 craters, and excluding those near to the centre or edge of the disk, that $a/b = 1{\cdot}02 \pm 0{\cdot}005$. This gives an earthward semi-axis of between 1·00 and 1·04 times longer than the mean radius of the limb—a result which is only just positive.

It cannot be argued that real differences in the chosen orthogonal diameters of craters will yield negligible effects on the final result provided a sufficiently large number of craters is investigated, for roughly parallel lines of weakness are known to exist all over the Moon's surface. This problem will be discussed more fully in Chapter 11; for the time being it may be assumed that the term

* For "lava flows" read "maria", and, for a discussion, see 14-3.

"lines of weakness" refers to the directions in which portions of the walls of craters are constrained. Instead of giving the geometrical elongation of the earthward semi-axis, Murakami might, in fact, have discovered a real general difference in the lengths of the axes of the craters.

Koziel (1950) suggested that the axis of the Moon's elongation was directed not towards the centre, but towards the southern hemisphere, of the Earth. Hopmann (1952d) performed new measurements on five of Franz' Lick plates and found that the position of the major axis was given by $\lambda = 0°$, $\beta = -8{\cdot}1$ and the position of the polar axis by $\lambda = 0°$, $\beta = +81°{\cdot}9$.* Hopmann also found the semi-major axis to be 7·0 km longer than the semi-minor axes (the radii of the limb). Thus, qualitatively, Hopmann confirms Koziel, but even qualitative results must depend on the selection of points on the Moon's surface.

From studies of the effect of libration on the Moon's radius, Yakovkin and others (1952c) detected that the mean radius of curvature† of the east limb was greater than that of the west limb by 0·14 seconds of arc.

Again using the data of Franz and Saunder, Engel (1957a) ordered the points in zones two or three degrees wide to either side of an artificial equator which stretched obliquely through nearly circular maria in the southern hemisphere. Unexpectedly consistent relationships were found, and Engel was led to propose that the Moon had a circumferential bulge, together with an axis longer than average which passed through or near to the crater Phocylides. Similar results were found by Engel (1959b) using the 150 of Franz' points revised by Schrutka-Rechtenstamm (1958a). The approximate location of the southern pole, defined with respect to these zones, was found to be $\lambda = -66°$, $\beta = -50°$.

3-2 The internal constitution of the Moon

If, instead of observing the positions of standard points on the lunar surface with the aim of determining the geometrical figure of the Moon, the same data are used to study the motion of the Moon, it is possible to deduce a little about the Moon's internal structure. Suppose that the Moon is an ellipsoid of principal moments of inertia

* For the definitions of λ and β, see 2-4.

† The report uses the terms "radius" and "radius of curvature", so it is not clear which is meant.

I_x, I_y, I_z. The z-axis points towards the Earth, the y-axis is the Moon's polar axis, and the x-axis is mutually perpendicular to these axes. $I_x \neq I_y \neq I_z$, and the motions which are observed are characterized by these differences.

Unfortunately, the presence of limb irregularities, which have been discussed above, precludes the estimation of I_z from the formula

$$I_z = \frac{m}{5}(X^2 + Y^2), \tag{3-2-1}$$

where m is the mass of the Moon, since X and Y—the semi-diameters of a section of the Moon in the x–y plane—are nearly equal, and neither can be measured with sufficient accuracy.

It is usual to let the polar axis be of unit length. Let the x-axis be of length $1 + \varepsilon_x$, and the z-axis of length $1 + \varepsilon_z$. Then, using equation (3-2-1), and the corresponding equations for I_x and I_y, and neglecting the very small quantities ε^2, it follows that

$$I_x = \frac{m}{10}(1 + \varepsilon_z), \tag{3-2-2}$$

$$I_y = \frac{m}{10}(1 + \varepsilon_x + \varepsilon_z), \tag{3-2-3}$$

and

$$I_z = \frac{m}{10}(1 + \varepsilon_x). \tag{3-2-4}$$

Using equations (3-2-2), (3-2-3), and (3-2-4),

$$\frac{I_x - I_y}{I_z} \approx -\varepsilon_x, \tag{3-2-5}$$

$$\frac{I_y - I_z}{I_x} \approx \varepsilon_z, \tag{3-2-6}$$

and

$$\frac{I_z - I_x}{I_y} \approx \varepsilon_x - \varepsilon_z = -\gamma, \tag{3-2-7}$$

say. A further useful definition is the ratio

$$f = \frac{\varepsilon_x}{\varepsilon_z}, \tag{3-2-8}$$

which is sometimes described as the mechanical ellipticity.

Some further quantities must be defined: I, the mean inclination of the Moon's equatorial plane to the ecliptic; i, the inclination of the Moon's orbital plane to the ecliptic, and μ, the mean motion of the node along the ecliptic with respect to the mean motion of the Moon.

With these definitions, and assuming that the Moon is a triaxial *homogeneous* ellipsoid, it may be shown (Tisserand, 1891) that, as a first approximation,

$$I = \frac{3i\varepsilon_z}{(1+\mu)(2\mu+\mu^2-3\varepsilon_z)}\sqrt{\left(1+\mu+\frac{\mu^2}{2}\right)}. \qquad (3\text{-}2\text{-}9$$

Weimer (1954a) has described how approximate values of I and f are assumed and used in the equations giving the physical librations, and how the corrections to these quantities are then found: first, observations of the *total* librations (l, b) are made, by plate measurements, and then the physical librations are calculated. Hence, using equation (3-2-9), ε_z can be calculated and ε_x can then be found from equation (3-2-8); γ may then be determined—though not very accurately—from equation (3-2-7).

Stratton (1910) re-reduced Schluter's (*Astr. Beob. Königsberg*, **28**, 19–39, 1856) observations of Mösting A, using certain constants derived by Cowell (1905b), and found that the difference between the results of Franz and Hayn (see Table 3-3-1) must be due to their observational materials and not to their methods of reduction. Stratton also showed that it was probably not necessary to suppose, when making reductions, that Mösting A did not lie on the mean sphere.

That there was a critical value (thought then to be 0·662, but now thought to be slightly larger) of the constant f which was connected with an instability in the Moon's physical libratory motion in longitude was noticed by Hayn (1906) and has since been discussed by Koziel (1948c) and by Jeffreys (1957b). In the last of a series of papers on the reductions and results of positional observations of the Moon, Koziel (1949d) reduced the values $f = 0{\cdot}73$ and $f = 0{\cdot}50$, by successive approximations, to the final values $f = 0{\cdot}71$ and $f = 0{\cdot}60$, respectively. These values have been confirmed independently by Belkovich and by Nefedjev (1952c), and again by Nefedjev and Habibulin (1955a). There were thus two roots for f, these roots lying one to either side of the critical value, but Khabibullin (1958c) removed the ambiguity from the solution for the mechanical ellipticity, and found the correct value to be $f = 0.60$.

The value of ε_z which can be found by this method may be called the *dynamical* elongation, to distinguish it from the *geometrical* elongation discussed above. It would seem to be smaller than the geometrical elongation (see Table 3-3-1), and the difference might be attributable to inhomogeneities in the Moon. However, on the assumption of hydrostatic equilibrium, Ramsey (1948b) has calculated that the value of I_y/mR^2 for the Moon, where I_y is the moment of inertia about the axis of rotation, m is the mass (given) and R is the calculated radius corresponding to this mass, is 0·398, and this approaches so closely the value 0·400, which corresponds to a model of uniform density, that the possibility of the Moon's possessing a large central condensation of heavy elements is excluded.

Urey, Elsasser, and Rochester (1959a) have found reasons for postulating that there exists a variation in the density of the material of the Moon with selenographic position; in this way they find that they can explain the presence of the observed surface irregularities and general non-equilibrium shape of the Moon even allowing for the fact that the deep interior of the Moon may not be rigid. The authors' argument hinges on data found by F. Boyd and F. Birch, on the melting points of silicates under pressure; data which indicate that partial melting should occur at the centre of the Moon.

3-3. The past history of the Moon

The *theoretical* elongation may be calculated by treating the Moon as being fluid, synchronous, homogeneous, and in a state of hydrostatic equilibrium. The theory for a circular orbit has been discussed by Tisserand (1891), who found $\varepsilon_x = 0{\cdot}0000094$, and $\varepsilon_z = 0{\cdot}0000375$; results confirmed by Jeffreys (1924; 1936; 1937; 1952b).

Jeffreys has shown that, with these assumptions, the semi-axes of the model are given by

$$\left.\begin{aligned} X &= \rho\left(1-\frac{10}{12}\frac{M}{m}\frac{\rho^3}{r^3}\right),\\ Y &= \rho\left(1-\frac{25}{12}\frac{M}{m}\frac{\rho^3}{r^3}\right),\\ Z &= \rho\left(1+\frac{35}{12}\frac{M}{m}\frac{\rho^3}{r^3}\right), \end{aligned}\right\} \qquad (3\text{-}3\text{-}1)$$

TABLE 3-3-1

Method	Authority	Date	ε_z	Elongation of z-axis (km)	f	I	ε_x
Theoretical	Tisserand	1891	$3{\cdot}8 \times 10^{-5}$	0·066	—	—	—
	Jeffreys	1924	—	0·041	0·49 ± 03	1°31′22″	$3{\cdot}00 \times 10^{-4}$
Geometrical	Franz	1899b	$(1{\cdot}14 \pm 3{\cdot}90) \times 10^{-3}$	1·98 ± 6·78	0·75 ± 04	1°32′06″	$4{\cdot}72 \times 10^{-4}$
	Mainka	1901b	$(4{\cdot}0 \pm 13{\cdot}0) \times 10^{-3}$	6·95 ± 22·59	0·50	1°29′37″	—
	Hayn	1902b	$2{\cdot}3 \times 10^{-3}$	4·00	—	1°31′25″ ± 10″	$3{\cdot}75 \times 10^{-4}$
	Pickering	1903a	$(1{\cdot}3 \pm 1{\cdot}2) \times 10^{-3}$	3·2 ± 0·8 (*continents*)	0·57 ± 04		
				1·3 ± 1·3 (*maria*)	0·71 *or* 0·60	—	—
	Saunder	1905a	$(5{\cdot}2 \pm 2{\cdot}7) \times 10^{-4}$ *or* $(1{\cdot}23 \pm 2{\cdot}90) \times 10^{-3}$	0·90 ± 0·47 *or* 2·14 ± 5·04	0·62 *or* 0·71	—	—
	Baldwin	1949c	$(1{\cdot}30 \pm 0{\cdot}12) \times 10^{-3}$ (*continents*) $(1{\cdot}17 \pm 0{\cdot}21) \times 10^{-3}$ (*maria*)	2·26 ± 0·21 2·03 ± 0·37	0·60 *or* 0·71	—	—
	Weimer	1954a	$(3{\cdot}35 \pm 0{\cdot}27) \times 10^{-3}$	5·82 ± 0·45			
Dynamical	Tisserand	1891	$6{\cdot}14 \times 10^{-4}$				
	Franz	1899a	$6{\cdot}14 \times 10^{-4}$				
	Hayn	1909	$6{\cdot}29 \times 10^{-4}$				
	Stratton	1910	—				
	Weimer	1949a, 1954a	$6{\cdot}25 \times 10^{-4}$				
	Koziel	1949d	—				
	Belkovich	1952c	—				
	Nefedjev	1952c	—				

where ρ is the radius of the mean sphere of the Moon, M is the mass of the Earth, m is the mass of the Moon, and r is the distance between the Earth and the Moon. These formulae give the following increments: $X - \rho = -0{\cdot}0011$ km, $Y - \rho = -0{\cdot}0027$ km, and $Z - \rho = +0{\cdot}0381$ km. Both Tisserand and Jeffreys have also shown theoretically that if the Moon solidified when it was a synchronous satellite (that is, when it turned a constant face towards the Earth) then $f = 0{\cdot}25$. (See, for example, Jeffreys, 1952b, pp. 158–159.)

It will be convenient at this stage to tabulate the results found by different investigators for the theoretical, geometrical, and dynamical elongations ε_z before proceeding to a discussion of the results. In Table 3-3-1, ε_z has been given as a ratio, and the estimated elongation has been given in kilometres.

Comparison of these results suggests that the theoretical value is not found in practice: the observed elongation is probably greater than would be expected. This means that the Moon is probably not a homogeneous ellipsoid in a state of hydrostatic equilibrium.

Furthermore, the agreement between the results of the two observational methods is poor. This may be due to the fact that the results of the geometrical method are not influenced at all by the distribution of matter within the Moon, whilst the observations of the Moon's dynamical elements take full account of the Moon's internal constitution, whatever this might be. These values are then substituted in an equation which is not quite correct if the Moon is not quite a homogeneous ellipsoid and hence the results found for ε_z will not be correct. Various models of the Moon may be constructed. A tentative conclusion is that either the inhomogeneity of the Moon is responsible for the difference between the geometrical and dynamical elongations of the earthwardly-directed semi-axis, or the face of the Moon which is not visible from the Earth contains low-lying areas of appreciable extent.

Jeffreys (1936; 1937) has remarked that, in all cases, the observed value of f is much greater than 0·25, and hence the Moon cannot have solidified when it was keeping a fixed face turned towards the Earth, but must have solidified when it was in a state of free rotation. Kuiper (1954b) came to the same conclusion, which should, however, be treated with caution in view of the fact that accumulation of

material by the Moon could change the value of f. Jeffreys concluded that it seemed necessary to attribute the possible ellipticity of the x–y plane section (the ellipticity of the limb) to the Moon's primitive axial rotation, and the positive value of $\varepsilon_z - \varepsilon_x$ (or the earthwardly-directed bulge) to "irregular changes arising after solidification". Urey (1952a) suggested a similar but more specific solution—that of differential deposits by impacts, and DuFresne (1956) has also suggested that the bulge is due to uneven accretion. In such an event, the bulge would orientate the Moon so that its longest semi-axis would eventually point towards the Earth.

However, although there have undoubtedly been both irregular changes and differential deposits on the Moon, at least on a minor scale, these suppositions conflict with Baldwin's suggestion that the tidal bulge in maria is the same as that of the continents: on these grounds it would seem that the bulge must have been produced by more uniformly acting forces, such as tidal action. Furthermore, the marial *surfaces* must be as old as the continents, and hence it would be very difficult to account for the maria as thick deposits of dust, as Gold (1955b) does. Baldwin (1949c) concluded, "It seems unavoidable that the Moon solidified very early in life and has been of the present shape ever since." He argued that the maria must therefore have been early lava flows. Again, in opposition to these views, DuFresne (1956) has pointed out that Baldwin's idea of highly fluid lava is incompatible with the apparent magnitude of the marial relief.

An aid to the solution of this difficult problem might possibly emerge from a critical study of the lunar global fracture system on the lines set out by Spurr (1948d) and by the author (1957c). It is thought that it would be premature to predict the past history of the Moon's motion with the knowledge at present at our disposal. Improved and more detailed measurements of the positions of points on the lunar surface would be very helpful, for such is the raw material which provides us with a knowledge of the true shape of the Moon. It is significant to note that the words of Pickering (1903a) still hold good: "In conclusion, we may say that . . . to determine the absolute heights and positions of the craters with the greatest accuracy now available, we need not only more original negatives, but we need also that they should be taken at times of greater libration."

3-4. Conclusions

Of eight measurements of the geometrical elongation of the z-axis of the Moon, only three results demonstrate that there *is* an elongation. The actual value of the geometrical elongation (see Table 3-3-1) depends on the selection of measured points.

Because the theoretical elongation appears to be smaller than the observed elongations, by at least an order of magnitude, the Moon is probably not a homogeneous ellipsoid in a state of hydrostatic equilibrium. The geometrical and dynamical elongations do not seem to agree, and it is suggested that, if confirmed, this may be interpreted to mean that the Moon is not homogeneous, or that there are widespread deviations of the level of the surface of the averted hemisphere from the level of the mean sphere.

Franz' measurements were based on a now obsolete theory of the librations, and 150 of his points have been revised, recently, by Schrutka-Rechtenstamm (1958a). Maria are not always lower than adjacent continental areas. In order to draw more significant conclusions about the shape and history of the Moon it is desirable that the number of original measured points be increased and that the measurements be made to a higher degree of accuracy. A modern rediscussion of all the older measured points might, nevertheless, still be useful.

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CHAPTER 4

The Luminous Intensity and Luminescence of the Lunar Rocks

4-1. Relative intensities in general: Albedo

At full Moon, the maria are only about three-quarters as bright as the continents (Pettit and Nicholson, 1930) and the Moon then sends us the most luminous energy, the exact amount varying from one full Moon to the next, but the intensity being, according to Russell, Dugan and Stewart (1945b), about 0·24 metre-candle. The stellar magnitude of full Moon they gave as −12·6 and this became −10 at the quarters (Russell, 1916a).*

At any phase, and for the same angle of illumination, the rays (the bright streaks which radiate from many craters) are brighter than the continents, and the continents are brighter than the maria. Crater walls are, in general, brighter than their bottoms. In very small craters it is not possible to see the floors (the critical size is set by diffraction) and such craters may in any case be either bright or dark. With very large craters, the wall brightnesses tend to approach the brightnesses of their floors. The brightness of the floor of the average crater decreases as the size of the crater increases as demonstrated by Daly (1946d), and there is a similar relationship for the walls of craters. Peal (1897) supposed that the greater the slope of a lunar mountain, the greater was its rate of erosion. It may be assumed, for the moment, that erosion of the lunar surface is caused largely by the action of micro-meteorites, and gravity. Other effects will be considered later. Peal noted that the steeper slopes—the inner walls of craters—were always brighter than the outer walls of

**Added in press:* A modern re-determination by Martynov (1960) of the integral stellar magnitude of full Moon, by photoelectric and spectrophotometric means, has yielded −12·54 for the visual magnitude (based on Zinner's star magnitude catalogue) and −12·71 for the photometric magnitude (U, B, V system: see, e.g., Johnson and Morgan, 1953c).

craters, and these, in turn, were brighter than any surrounding mare-base materials. He was therefore led to suggest that the maria were covered with a thin layer of dust and that the walls of craters had been left partially bare of such dust.

The albedo* of the Moon may be defined as the ratio of the total amount of radiative energy reflected from it, in all directions, to the total amount of radiative energy incident upon it. It would obviously be difficult to determine the albedo of the Moon with great accuracy. Russell (1916b) estimated the visual albedo to be 7·3%. Using a potassium cell, Rougier (1936) found a value—which must differ but little from the photographic albedo—of 5·4%. Determining the Moon's visual albedo radiometrically (that is, with a thermocouple), Pettit (1945) found a value of the order of 10%. It seems that, on average, the surface of the Moon does not reflect more than 10% of the light incident upon it, although the average rock composing the surface may well be a better reflector, due to the rough nature of the surface and the consequent loss of light by absorption. According to Kosyrev (1956e) some regions of the Moon have albedos as large as 30–40%. Beckett's (1931) measurements on building materials show that only rough brown or black tiles, or very dark coloured bricks, have albedos as small as about 10%. Armellini (1927b) determined the ratio of the average brightness of the seas to that of the continents, from 700 observations, the regions selected being always at the same distance from the centre of the disk so that the relative brightnesses were independent of the law of reflection across the disk, and found 0·48. Accepting Russell's value of 7·3% for the mean visual albedo of the seas and the continents, he found the average albedo of the seas to be 4·8%. Armellini remarked that this value was identical with that of the lava of Etna, and close to that of Vesuvius' lava. However, Armellini's figure of 0·48 is smaller than Pettit's and Nicholson's (about 0·75): this agrees better with the estimates of the relative reflecting powers of dark and light regions made by Wilsing and Scheiner (1909), which vary from 0·6 at 4500 Å to 1·0 at 6400 Å.

A list of the absolute albedos of many mare and continental points, and those of some craters, was published by Sytinskaya (1953a).

4-2. Intensity distribution across full Moon

The telescopic appearance of the limb of full Moon is that it is

* For special definitions of albedo, see the works cited.

brighter than the rest of the disk. Evidently, part of this appearance may be attributed to the phenomenon of contrast with the sky background, but it is seen from a photometric trace across the equatorial regions made by Pettit and Nicholson (1930), and reproduced in Fig. 4-2-1, that, although the centre of the disk is 10–15% brighter than the limb at the points measured, the limb itself is in fact some 60% brighter than the adjacent maria. Markov (1928) found similar relationships.

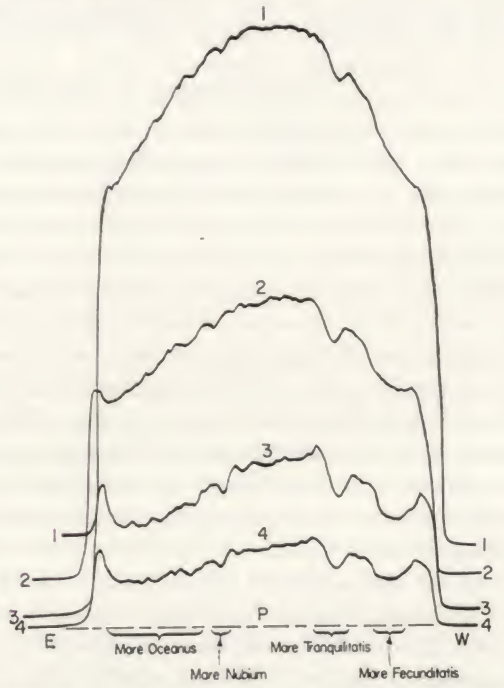

FIG. 4-2-1. Brightness distribution across the equatorial regions of a full Moon: Pettit and Nicholson (1930). Curve 1 represents free radiation; curves 2, 3, and 4 represent the radiation passing through a fluorite filter, a glass filter, and a water cell, respectively. (See transmission curves of Fig. 7-3-3.) (*Astrophysical Journal*)

If Lambert's law of diffuse reflection $I \propto \cos r$ were to hold for the lunar surface, where I is the luminous intensity at any point on the surface and r is the angle of reflection of light at that point, one could expect to find appreciable limb darkening at full Moon, although the actual appearance would depend on the particular law of incidence

assumed. The Moon approximates, however, to the diffuse reflection law of Lommel-Seeliger,

$$I \propto \frac{\cos i}{\cos i + \cos r},$$

or to the law of Euler,

$$I \propto \frac{\cos i}{\cos r},$$

where i is the angle of incidence of sunlight at the point in question.

The real brightness of the limb with respect to adjacent areas is due to the screening of marebase materials by the brighter mountains, and the fact that the rays trespass on elevations and are apparently crowded together when the limb is viewed. Any luminescence of the rays would also tend to increase the brightness of the limb.

4-3. Variations in the intensities of the continents, the maria, and the rays, with variation of phase angle: Models of the surface of the Moon

Figure 4-3-1 shows the relationship between the intensity of the integrated light of the Moon, the intensity of full Moon being taken as the unit, and the phase angle, according to Russell (1916a). The relationship between the stellar magnitude of the Moon and the

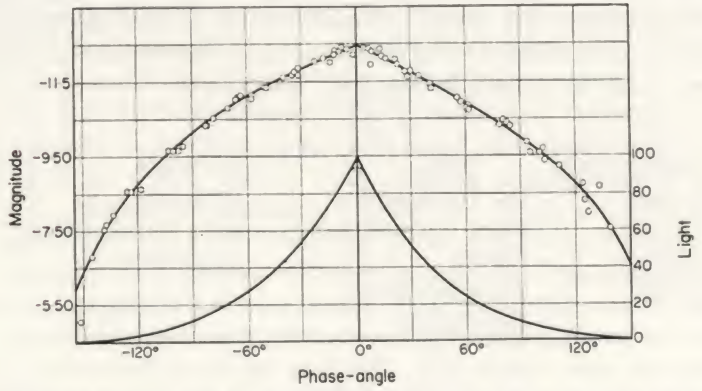

FIG. 4-3-1. Variation of the intensity of the integrated light of the Moon with the phase angle: Russell (1916). (In lower curve, 100 units = intensity of full Moon.) (*Astrophysical Journal*)

phase angle is also given. Proportional values of intensity were plotted earlier by Parsons (1873), and Rougier (1933) constructed a curve from photoelectric observations. Pettit (1945) has revised the older measurements (Pettit, 1935b) to arrive at a radiometric magnitude of —13·1 for full Moon. Pickering (1908) determined the phase-brightness curve by means of a shadow photometer, and calibrated his curve by observing Arcturus. He attributed a stellar magnitude of about —12·5 to full Moon and Russell found the figure —12·6. King (1912) from measurements on nearly 100 plates, and by comparison with Polaris, found the photographic magnitude of full Moon to be —11·2, and of the quarters, —9·0. The intensity-phase curve for the continents probably lies close above the curve given in Fig. 4-3-1 for the general surface; that of the seas must lie below it.

A thorough investigation into the brightness variations of twenty lunar formations was made by Wirtz (1915). He plotted graphs of F against the observed brightnesses,* where

$$F = \frac{\cos i \,.\cos r}{\cos i + \cos r} = \frac{\sin h_{\odot} \,.\sin h_{\oplus}}{\sin h_{\odot} + \sin h_{\oplus}}.$$

Here, as in (4-2), i is the angle of incidence of sunlight at any point, and r is the angle of reflection. The symbols $h_{\odot}$, $h_{\oplus}$ represent the selenographical altitude of the Sun, and of the Earth, respectively. This formula had the effect of rendering the observed brightnesses independent of the librational modifications of the quantities $h_{\odot}$ and $h_{\oplus}$. The maximum brightnesses of some of the measured formations occurred at the following local lunar times:

Before Noon	*Noon*	*Afternoon*
Kepler	Oc. Procellarum	Langrenus
Grimaldi	Mare Tranquillitatis	Mare Foecunditatis
Werner	Plinius	Aristarchus
Lexell	Mare Serenitatis	
	Sinus Medii	

In fact, the tendency was for a formation in the eastern hemisphere to attain its maximum brightness before the Sun attained its maximum altitude over that formation, and for a formation in the western

* In magnitudes, the signs being opposite to those of the usual convention.

hemisphere to be brightest after the Sun had passed its maximum altitude. The effect therefore tends to exhibit symmetry. These results are reflective of the rough nature of the ground: one would not expect a smooth planet to behave in this way.

Tycho behaved differently from all the other formations; the intensity actually fell gradually to a minimum in the late morning and early afternoon, and then rose again. Wirtz said that this was due to the fact that the central mountains reflected an essentially constant amount of light throughout the lunation.

Visual observers repeatedly discuss the apparent darkening of the floor of Plato around local noon. Wirtz cleared up the problem in 1915 when he wrote ". . . without doubt, the brightness rises rapidly until the Sun's altitude is 20°, and then remains nearly constant . . . to diminish slowly only when the altitude of the Sun gets less than 20° again". It appears that, since the surroundings must increase in brightness at solar altitudes greater than 20°, the apparent darkening of the floor of Plato must be due to the phenomenon of contrast. The appearance or non-appearance of small craters inside Plato will also depend on the prevailing intensities of the surrounds. The general results of Wirtz have been confirmed by van Diggelen, by photometric studies of five Yerkes plates (1946e).

Barabascheff (1923) gave some records of the intensity variations, corrected for atmospheric absorption, of certain maria. The characteristics of these curves—except that for Mare Tranquillitatis—could be explained by assuming that all seas were covered with a network of cracks, taken, for the purposes of calculation, to be of constant breadth and distance apart, and of infinite depth.

Soon afterwards Barabascheff (1924a) found, that if spherical pits were present on the Moon, they would give a good approximation to the observed curves. Again, from extensive investigations of the Moon's brightness variations, Schoenberg (1925) *assumed* that Lambert's law held for the Moon and hence *deduced* that the marked variability of the brightness of the central portions of the Moon's disk could be explained if it were assumed that the surface was liberally punctured with hemispherical depressions, the regions between these depressions being convex upwards. This result held for both continents and maria. For the rays Schoenberg said that, as for bright craterlets, the holes would have to be of such a form that light could reach their bottoms only at very small angles of incidence.

He pointed out that "no liquid, fluid, or dust-carrying atmosphere would prevail, because in these cases the holes would be filled in". Two practical illustrations of such a surface were (a) loose stones, set thickly together, (b) perforated lava. It is curious that Schoenberg did not suggest that there were large numbers of very small craterpits.

Barabascheff (1927a) has given a table showing the relative intensities of thirty-one chosen points for different values of the angle of incidence, the angle of reflection, and the phase angle. He found that the maximum brightness of any point occurred not when angle of the incidence was zero, but when the angle of incidence was equal to the angle of reflection; the maximum intensity of *any* point occurred near to the time of full Moon. Markov (1924b) found that the law of Fessenkoff,

$$I \propto \frac{\cos i}{(\cos i + \cos r)(1 + \cos^2 \alpha)},$$

where α was the angle between the incident and reflected rays, could explain all the characteristics of the Moon's surface. Since Fessenkoff's or Lommel-Seeliger's laws were obeyed, then the brightness of lunar details at full Moon depended, said Markov (1926), on their reflecting powers, and not on their relief: Barabascheff (1927a) said that, if all regions of the Moon had the same coefficient of reflection, then the Moon's albedo should be determined at full Moon, when the Moon would appear as a uniformly bright disk.

Schoenberg (1929) found that the integrated-light variation could be represented by the expression

$$I \propto \frac{\cos i . \cos r}{\cos i + \lambda \cos r},$$

with $\lambda = \frac{1}{3}$ for angles of incidence less than 75°. For angles of incidence greater than 75°, this law broke down unless λ was varied. It was preferable, he said, to use a constant value of λ and to multiply the above expression by a function expressing the amount of intensity to be subtracted on account of shadows. Schoenberg plotted curves of this "shadow-function" for the continents, maria, and rays, using the observed intensity-phase curves of Barabascheff and Markov. The curve for the rays was strikingly different from the curves for the other parts of the surface: for the rays the shadow function assumed a characteristic value which decreased rather abruptly at phase angles

close to full Moon, whilst for the continents and maria the function increased uniformly with increasing phase angle, for phase angles up to at least ±90°. This again seems to indicate that the rays are composed of bright pits. An empirical formula for the intensity distribution across the sunlit disk of the Moon at different phase angles was constructed by Öpik (1924).

Measuring the relative intensities of fifty-nine areas at eleven phase angles on Lowell Observatory plates, with a densitometer, Bennett (1938) confirmed Wirtz' (1915) and Barabascheff's (1923) conclusions that each point on the lunar surface had its maximum brightness at phase angles not far removed from 0° (full Moon). Bennett also found that, in general, a formation in the eastern hemisphere showed an abrupt rise in intensity to a maximum close to full Moon, with a subsequent gradual fall in intensity, and that the behaviour of a formation in the western hemisphere was symmetrical with this.

Considering Schoenberg's (1925) model of the Moon's surface, Bennett (1938) deduced that, for angles of reflection smaller than 10° (i.e. near to the centre of the Moon's disk) spherical pits did not represent the observations so well as prolate spheroidal pits, the ratio of the lengths of the major and minor axes being 1·8, and the major axis being directed towards the centre of the Moon. Models such as Schoenberg's and Bennett's, which rest on the poor assumption that Lambert's law holds for the Moon, and which demand a different surface structure as one proceeds away from the central portions of the Moon's disk, are clearly very artificial.

Considering the *whole surface*, the author constructed two geometrical models, one representing a spherical surface of radius R coated uniformly with hemispherical protuberances, and the other representing the same surface coated with hemispherical concavities. These hemispherical lumps and pits were taken to have radii which were equal, and small in comparison with R, but large in comparison with the wavelength of light. It was found that neither model gave intensity-phase records which accorded with those known for the Moon.

4-4. Intensity variations of bright and dark spots

Many spots—bright against a darker background, or dark against a brighter background—appear to vary in intensity in anomalous

fashions. In general, the variations are out of phase with the background, and are probably real in some cases.

Williams (1898) noted visually the brightness-variations of two dark spots in Atlas, one of which appeared to be brighter when the Sun was low than when the Sun was high. He referred the apparent brightnesses to a scale of magnitudes introduced by W. H. Pickering: in this scale, +0·1 magnitude corresponded with the very bright central mountain of Aristarchus, and +6·0 magnitude corresponded with black shadow. Williams made no attempt to explain his observations.

Of more importance are the visual estimates of the periodic changes in the relative brightness of four light spots in Schickard. These estimates were made independently by six observers, and their results have been collated and reported by Emley (1937). The spots will be designated α, β, γ, and δ, in accordance with a chart drawn by Emley (1934).

Spot α remained fairly constant in relative brightness during a lunation. (The relative brightness was defined as the excess of brightness over the mean brightness of the four spots); β and γ increased uniformly and considerably, whilst δ showed a large decrease. Emley wrote "That the halos of four neighbouring ... craterlets ... should behave in such a different manner ... is very surprising; it evidently points to some interesting differences in the nature, or physical condition, of the materials composing these bright areas." These estimates were referred to the scale in which 0° designates black shadow and 10° corresponds with the central mountain of Aristarchus. In spite of the apparent changes in brightness described for these spots, Emley's graphs relating the probable real changes in intensity to the phase-angle show that all four spots attain maximum brightness when the Sun rises fairly high. Variations such as these are probably due to the sunlight being reflected from differing slopes.

The real brightness of the white patch which surrounds Linné has been suspected to show variability. W. H. Pickering believed that it brightened during an eclipse of the Moon, but decisive evidence is lacking. The question as to whether Linné itself has changed has been discussed elsewhere (9-6).

A rapid variation in the apparent brightness of a lunar peak was noticed by Houghton and confirmed and reported by Warner (1955).

This peak was on the east wall of Cavendish and was just catching the rising Sun. Its intensity varied periodically, with maxima separated in time by about $\frac{2}{3}$ sec, for some 10 min, the variation becoming less noticeable as time elapsed. The seeing was reported to be good, but this was judged, presumably, with reference to the Moon, an extended object. Hence, that what was effectively a point source on the dark side of the terminator was being affected by the seeing can not be ruled out. It would have been interesting to have had a comparison record of the apparent intensity fluctuations of a nearby star.

4-5. The colour and intensity of the ashen light

The ashen light is sunlight which reaches the observer from the night hemisphere of the Moon after having been modified by "reflection" from the Earth. (Strictly, processes other than reflection are involved.) If the observer is on the surface of the Earth, the ashen light has passed through the Earth's atmosphere three times and has been modified accordingly, thus differing in character from pure sunlight.

Tikhoff (1914) studied the colour and intensity variations of the ashen light as functions of phase-angle. He found that, for a given phase-angle, the ratio (brightness of moonlight): (brightness of ashen light) increased with the wavelength of the light. Hence the moonlight was richer than the ashen light in light of long wavelength, and sunlight very probably became bluer after reflection from the Earth.

Figures given by Tikhoff indicate that the ashen light is very roughly of the order of 4000 times fainter than moonlight, but an analysis by Dubois (1958b) shows that there is a seasonal variation of the brightness of the ashen light, due to the variation in the amount of cloud covering the Earth, and also a variation arising because of the fact that the Earth's seas appear to be brighter than its continents.

4-6. Do the Moon's rocks fluoresce?

That the light of an eclipsed Moon varies appreciably in intensity from eclipse to eclipse is well known. Lowe (1884a) remarked on the darkness of the eclipse of 4 October 1884—especially the total phase—as compared with that of previous ones. Burder (1884b) also noticed that this was an unusually "dark" eclipse, and asked

"Is it possible that the surface of the Moon may be in some small degree self-luminous, and that a variation (from unknown causes) in the degree of this self-luminosity may account for the difference observed in the visibility of the Moon in two eclipses . . . ?" Again, a paragraph from the "Scientific News" column of the *English Mechanic* (1918) reads "Several observers of the total lunar eclipse of 4–5 July, 1917, reported that the brightness of the lunar disk appeared much greater around the limb than near the centre. These observations led M. A. Nodon, of Bordeaux, to revive a suggestion that has sometimes been made to account for the brilliancy of certain lunar craters, viz., that the surface of the Moon may possess a luminosity of its own in the nature of phosphorescence. In that case, perspective would increase the apparent luminosity toward the limb."

These questions have been investigated fairly well. Not only has the phenomenon of luminescence shown itself in quantitative results; there are also good reasons (which are discussed in the next section) for suggesting that Burder's "unknown cause" is radiation originating in the outer parts of the Sun.

4-7. Evidence for the phenomenon of luminescence

Link (1932) produced a theory which described the intensity of the various parts of an eclipsed Moon, and this theory discounted any luminescent properties of the Moon's rocks. After studying the brightness of the Moon during eclipses, by photographic photometry, Link (1946a, 1946b) noted that, in some eclipses, the penumbra was brighter than its theoretically derived value, and he attempted to explain these differences via the properties of the Earth's atmosphere. However, shortly afterwards, Link (1946c) found that refraction in the Earth's atmosphere could not explain the observed excesses of illumination from a quantitative point of view: the outer parts of the Sun were too faint to account for the observed penumbral intensities. He was thus led to propose that the difficulties may be settled by supposing the Moon to be in some degree self-luminous. He noted that the solar corona would be less eclipsed than the disk of the Sun for an observer situated in the penumbra at a point not far from the umbra, and that the corona was the source of ultraviolet radiation which may excite minerals on the Moon's surface. On the other hand, it was just as reasonable to suppose that corpuscular streams played their part, and the nature of the exciting radiations remained an open

question. Dubois (1958a) has commented that the ultraviolet solar radiation and the corpuscular radiation from the Sun may produce different characteristic emissions from the lunar rocks, but no positive information on this point has been forthcoming up to the time of writing.

In confirmation of Link's findings, Cimino (1957a), using a 6″·5 astrograph, found, by photographic photometry, an excess of light (with respect to the intensity given by Link's (1932) theory) in the penumbras of the eclipses of 29–30 January 1953 and 18–19 January 1954, but not in the eclipse of 15–16 July 1954. The excess was greater in the 1953 eclipse, and varied, in the penumbra, with the distance from the edge of the umbra.

Further research by Link (1950) yielded the following results: (a) the observed stellar magnitudes of points in the penumbra of an eclipsed Moon may have been in excess of the theoretical values by from $0^{m}{\cdot}5$ to $0^{m}{\cdot}75$; (b) it followed, from the observed excesses of illumination in the penumbra, that as much as 10% of the light of full Moon may have been due to luminescence; (c) there was a good correlation between the brightness of the Moon and the probable variations of the solar constant, the intensity variations on the Moon being some twenty-six times greater than the variations in the solar constant (Link, 1956d). This last point can carry little weight, however, because any variations in the solar constant, if they exist, are extremely difficult to detect.

In conclusion, Link mentioned the possibility of observing the residual intensity in the Fraunhofer lines of the lunar spectrum, a suggestion which was followed by Kozyrev (see below) and, in principle, by Dubois.

Dubois (1956b) compared spectrograms of the Moon, covering all visible wavelengths, with those of diffused sunlight. (The sunlight was diffused by allowing it to fall on some magnesium oxide.) He then measured the depths of the absorption lines, defining the depth of a solar line as $R = i_1/i_2$, where i_1 was the intensity of the blackest part of the line and i_2 was the intensity of the adjacent background light ($i_2 > i_1$). With an intensity i superimposed on the lunar line, the depth of the corresponding lunar line would be $R' = (i_1 + i)/(i_2 + i)$. It followed that, if luminescence were present, $R' > R$. The spectrograms were of different dispersions. Dubois said that interpretation was "delicate", because the spectra which had the correct amount of

photographic blackening were of small dispersion and did not allow the depth R to be measured with the accuracy desired: spectra of large dispersions had insufficient blackening, and again R could not be measured accurately. Dubois found that parasitic light and light scattered by the atmosphere of the Earth could be neglected. His results were very tentative, and only qualitative, but, from some spectrograms taken by Righini at Arcetri Observatory, in Italy, Dubois claimed to have detected fluorescence of the following sunlit regions in the colours indicated. (The list has been supplemented by some later results of Dubois, 1956c.)

red	Oceanus Procellarum.
red and yellow	Regiomontanus (floor).
red and green	Mare Humorum.
red, yellow and blue	Mare Tranquillitatis, Sinus Medii, Tycho, Mare Serenitatis.
red, yellow, blue and violet	Mare Imbrium.
yellow and green	Mare Crisium.
yellow and blue	Mare Nubium.
green	S.W. limb.
no fluorescence detected	Copernicus.

In a later paper, Dubois (1956f) analysed the results of different observers who had used different spectrographs and different photographic plates. An examination of eighty-six regions revealed that forty-six showed a definite luminescence, twenty-four at 6560 Å, twenty-six at 5893 Å, four at 5200 Å, twenty-one at 4861 Å and ten at 4300 Å. He found that greater accuracy could be achieved by using a spectrograph of fairly large dispersion.

The seas generally showed more luminescence than the continents, but this was probably due to the small albedos of the seas. The amount of luminescence of a given region appeared to vary appreciably with time.

Laboratory tests showed that certain bands of luminescence emitted by the lunar rocks could be associated with certain minerals. Thus, regions which showed a green luminescence could be associated with willemites, cadmium or beryllium silicates, or phenacites. Dubois noticed that the edges of seas showed a green luminescence, but the luminescence of such regions varied little, in intensity, with wavelength. (This is not the first time that special properties have been

attributed to the borders of seas: see Chapter 5.) Other patches of the Moon showed a characteristically quite strong luminescence in yellow and red light, together with a strong absorption of luminescence in green light. Considerably extending this work, Dubois (1959c) observed, in general, two types of luminescence-band. The wider bands (of widths about 200 Å) were usually associated with lunar regions emitting a green luminescence (at about 5300 Å), and could be identified with the bands of willemites, and of silicates of the alkaline-earths (admixed with less active minerals). Narrower bands, which could not be identified with those of particular minerals, could be explained by the superposition of absorption and emission bands.

Dubois also noted that the characteristic bands of the rare earths and of the salts of uranium were absent in the lunar spectra.

Establishing the existence of the phenomenon of luminescence of the lunar rocks beyond doubt, Kosyrev (1956e) compared the profiles of the Fraunhofer absorption lines of the Sun's and the Moon's spectrum.

Kosyrev searched first for auroral phenomena around the limb of a new Moon, using the 50-in. reflector of the Crimean Observatory in conjunction with a photographic spectrograph, the slit of the spectrograph being perpendicular to the limb. Exposures of one hour were given at f/4.* The spectrum of the ashen light was found to be strong in comparison with the sky spectrum adjacent to the Moon and it was concluded that, for practical purposes, the Moon could have no ionosphere and no magnetic field,† and, therefore, that solar radiation would fall unimpeded and undeviated upon the Moon's surface to cause luminescence of the minerals which were present.

It was decided to investigate the H and K lines (3969 Å and 3934 Å), respectively, of ionized calcium (Ca II), since luminescence, if present, would be seen most easily in the ultraviolet, where the intensity of both sunlight and moonlight decreased markedly. Spectrograms were taken with the 50-in. telescope with a dispersion of 50 Å mm^{-1} around the H and K lines, and with a slit 0·05 mm wide. The exposures

* "At f/4" means that the work was conducted with the ratio of the focal length of the telescope to the clear aperture of the mirror equal to 4.

† Both the Russian probes Lunik I (which passed within 6000 km of the Moon's surface) and Lunik II (which crashed on the Moon) later failed to detect a lunar magnetic field in excess of 10^{-3} oersted. A theoretical discussion of possible magnitudes of the lunar magnetic field has been given by Vestine (1957b).

varied from 2 to 10 minutes for the visible part of the spectrum and from 30 to 40 minutes for the contours of the *H* and *K* lines. The solar spectrum was photographed with the same equipment and on the same days, when possible, and exposures as long as 0·2 to 10 sec were used by diaphragming the telescope down to 20 holes evenly spaced and each 4 mm in diameter. In this way, it was possible to obtain equal densities of the continuous backgrounds of the spectra of the Sun and the Moon.

If the intensity at any particular wavelength in the Moon's spectrum is $I_{☾}$ and the luminescence at this wavelength is of intensity i,

$$I_{☾} = k(I_{\odot} + i), \tag{4-7-1}$$

where $I_{\odot}$ is the intensity at the same wavelength in the spectrum of the Sun, and k is some constant determined by the condition that the intensity of the continuous spectrum is normalized, so that

$$I_{☾} = I_{\odot} = 1.$$

Using this special condition in equation (4-7-1), it follows that

$$k = \frac{1}{1+i}. \tag{4-7-2}$$

Hence, using equation (4-7-2) in equation (4-7-1),

$$I_{☾} = \left(\frac{1}{1+i}\right).I_{\odot} + \frac{i}{1+i}. \tag{4-7-3}$$

On measuring the profiles of the lines, and plotting $I_{☾}$ against $I_{\odot}$, Kosyrev found the relationship to be linear with a positive intercept. By means of equation (4-7-3), the amount of luminescence present in any particular case could be determined from the observed intercept.

Spectra of maria, continents, Wood's Spot, and the craters Plato, Schickard and Copernicus were studied, but all of these regions gave a negative result. Only the system Aristarchus-Herodotus, taken as an example of a ray-system, showed a definite amount of luminescence. This varied in intensity, with time, and the luminescent intensity was greatest after full Moon, for a given amount of solar activity, sometimes attaining 13% of the intensity of the rays at the same wavelength. At all phase angles, the luminescence in the *K* wavelength was one-and-a-half times greater than that in the *H* wavelength.

Kosyrev concluded that there was a luminescent substance situated at the bottoms of small depressions connected with the rays of Aristarchus, and that this substance did not contain even negligible amounts of iron, because iron was "a very active extinguisher of luminescence". Furthermore, the substance must, in order to exhibit luminescence, have a very low temperature (probably <0°C). A patch of the lunar surface having such a low temperature when the Sun is high above it must be sufficiently bright to reflect much of the heat which is falling on it, because the temperatures attained by lunar rocks when the Sun illuminates them normally are of the order of 100°C. Kosyrev was thus led to believe that the luminescent substance must have had a very large albedo: about 0·3 to 0·4, of the order of the visual albedo of white sand. It was difficult to say what the substance might have been: some variety of quartz was suggested. In any event, it must in time be covered by meteoritic dust. On the assumption that 1 ton of micromatter fell on the Earth in 24 hours, Kosyrev suggested that the last period of ray-formation on the Moon was $\gtrsim 5 \times 10^7$ years ago.

4-8. An eruption in the lunar crater Alphonsus

Because Alter had suspected the presence of gases inside Alphonsus (see 8-1) Kosyrev (1959a) determined to investigate Alphonsus with the spectrograph and 50-in. reflector mentioned in the previous section.

With a linear dispersion of 23 Å mm^{-1} in the region of the $H\gamma$ line, and with the entrance slit of the instrument pointing from east to west, across the sky, he guided on the central peak of Alphonsus, and took spectrograms, on Kodak 103a-F emulsion, on many occasions without detecting anything unusual. However, whilst one such spectrogram was being taken at 01 h U.T. on 3 November 1958, the central peak became "strongly washed out and of an unusual reddish hue". At 03 h 00 m U.T., a second lunar spectrogram was commenced. This exposure lasted for half an hour, up to 03 h 30 m, and Kosyrev noted that the central peak of Alphonsus looked unusually bright and white. During this exposure, the brightness fell to its normal value. A third spectrogram was then taken, from 03 h 30 m until only 03 h 40 m U.T. On development, the first two spectra deviated from the normal appearance characterized by all previous

spectra and by the third one. The first spectrogram showed that, in violet light, the central peak was much less bright than usual (compared with adjacent parts of the crater), and the second spectrogram showed broad emission bands. Examining Alphonsus on the next night, Kosyrev found that Alphonsus remained normal.

Kosyrev has proposed the following interpretations of these observations. First, there was an ejection of a reddish-coloured volcanic ash, or dust, in the vicinity of the central peak of Alphonsus. This was followed by an efflux of gas, lasting for a time $0{\cdot}5 \text{ hr} < t < 2{\cdot}5 \text{ hr}$, which gave rise to the observed emission spectrum. The gas, he said, could have come from magma rising to the surface of the Moon. A prominent emission band, due to the C_2 molecule, had its maximum intensity at 4737 Å, gradually fading towards the violet end of the spectrum. The presence of carbon molecules was confirmed via other Swan bands with maxima at 5165 and 5636 Å and, in the Hδ region, a system of faint bands due to the C_3 molecule could be detected. There was no evidence of the presence of CN molecules which, like carbon molecules, are characteristic constituents of comets.

The actual emission is said to have been centred about 1·5 km to the east side of the central peak, nearer than the peak to the setting Sun. Kosyrev said that probably the Sun's ultraviolet light could penetrate only a short distance into the cloud. He estimated the thickness of the gas cloud to be of the order of 1·3 km.

Strong doubts have been cast on these conclusions. Kuiper (1959d) has stated that the 4737 Å Swan band would have been in absorption had C_2 been observed. The copies of the spectra which the author has seen are difficult to interpret. Certainly, one would not expect to find carbon in terrestrial volcanoes. Gaydon and Learner (1959e) have found that an escape of even quite cold gas from beneath the Moon's surface could show an emission spectrum; so this may not have been a lunar volcano, even if the observations are perfectly correct.

Assuming that there was a layer of dust on one part of the Moon's surface, and also that the rocks, here, contained two parts per million of uranium (a high value), Fremlin (1959b) reached the conclusion that $T \approx 24\sqrt{h}$, where T is the temperature in degrees C and h is the depth in the dust in cm, and hence that the temperature would be as high as 240°C at only 100 cm depth, and at the melting

point of basalt at a depth of only 25 m. Conduction to the sides of a dust-filled crater would be important and this, he said, would give rise to central volcanic activity, thus explaining Kosyrev's observations.

These figures are quite incompatible with measured sub-surface temperatures (see 7-3 and 9-4), but the lower temperatures which have been measured are average values for large areas of lunar surface, and do not apply to specific patches of lunar terrain. *Qualitatively*, there seems no doubt that Fremlin's hypothesis is correct.

Finally, Windsor (1959f) has suggested that any free radicals in the lunar rocks could react exothermically if subjected to an unusually intense burst of solar corpuscular radiation: this could provide yet another way of explaining Kosyrev's observation.

4-9. Summary

The albedo of the Moon, considered as a whole, is of the order of 10%. The darker terrains have albedos of the order of 5%, and the brightest patches of surface may reflect as much as 40% of the incident light. These reflectivities suggest that maria are composed of a substance as dark as some volcanic lavas and that some patches of the surface are as bright as granite.

The observed variation of the light reflected from particular spots indicates that the detailed structure of the Moon's surface is far from smooth. The rays seem to be composed of small, bright pits.

At a given time, the brightness of a particular spot on the lunar surface depends not only upon its reflectivity and the angles of illumination and viewing, but also upon the brightness of the earthlight (significant in the lunar night) and on the amount of luminescence of the spot, which is sometimes appreciable when it is being illuminated directly by the Sun.

In view of Kosyrev's observations of a gaseous emission from the crater Alphonsus, some of the older reports of volcanoes on the Moon—usually dismissed as illusions—should possibly be reconsidered. It should be remembered, however, that up to date Kosyrev is the only person who claims to have positive proof that the Moon is no longer to be considered completely inactive, and that his evidence does not satisfy all astronomers.

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CHAPTER 5

The Colour of Moonlight and the Composition of the Moon's Surface

5-1. Visual work

Many workers have indicated that much may be learned about the composition of the Moon's surface by photographing it in light of different wavelengths and comparing the relative intensities of the photographs with those of laboratory specimens treated in the same way. In this manner, outstanding colour-differences in the intensities of certain parts of the Moon have been detected and inferences have been drawn about the compositions of the lunar rocks.

One of the earliest workers in this field was Kruger (1903) who demonstrated the uses of colour filters for investigating the nature of planetary surfaces, and reported that the lunar plains had a "well-known" greenish colouration. Visual comparative estimates, by the use of colour screens, were made by Warth (1922) who found that the floors of Clavius and Longomontanus were "mauve", that the area west of Clavius was mottled, consisting of brown areas on a blue background, and that the southern slopes of Maginus were "intense green". These things do not show on the colour photographs available (see below) and are probably not reliable. Pickering (1924b) has also pointed out some colour differences, including a reddish-brown area inside Stevinus "visible only before the sunlight reaches the bottom of the crater". This observation was mentioned by Haas (1942a) who maintained that the colour variations in Stevinus and its neighbour Snellius were too small to be studied successfully, but that the relative intensities of the *shadows* in these craters varied with time. Different shadings of shadows have also been pointed out by Avigliano (1953b).

Haas (1937) has given a summary of the visual observations of many workers on different craters. Their observations confirm, for

example, that the floor of Grimaldi is green at sunrise, that brown patches appear on the walls at 12 hr after sunrise, whilst the most frequent appearance, setting in at 32 hr after sunrise, is of a greenish-grey floor and brownish-purple walls, the purple tones being most easily seen just after full Moon. After full, the green intensity varies irregularly, and just before sunset both colours fade into grey. Haas' conclusion is that the colour changes represent a general phenomenon affecting the entire surface. Later Haas (1942b) concluded that the low-Sun colours were more striking than the colours under a higher Sun (a conclusion not to be verified by photography), but were nevertheless more transient, greens predominating in dark crater-floors. Under a high Sun the colours were very inconspicuous, but very stable.

Avigliano (1954) has presented an interesting account of colours observed visually, and has given rough charts to illustrate the colour-differences. He maintained that powers of greater than about fifteen per in. of aperture were of no advantage in detecting the vague lunar tints. He confirmed all of his visual work with the aid of colour photographs taken at different phases, and seems to have confirmed in a qualitative manner Miethe's and Seegert's (1911) work on the colour-phase variation of Mare Tranquillitatis (see below). He also pointed out the reddish-brown colour of "the diamond-shaped area to the north-east of the crater Aristarchus", without having known, it appears, of the previous work on this region (Wood's Spot).

All such visual work is interesting in so far as it demonstrates that there are on the Moon real colour differences. Different observers, however, see different colours in the same places at the same times, and it is obvious that serious qualitative work must be left for instruments.

5-2. Instrumental methods and results

The work of analysing the lunar rocks was put on a firm basis when Wilsing and Scheiner (1909) made an extensive comparison between the spectrophotometric properties of two selected lunar landscapes and terrestrial rock specimens, the latter being in their natural states of unequal forms. The albedos of certain terrestrial substances as determined by Wilsing and Scheiner are given in Table 5-2-1.

TABLE 5-2-1

Chalk	1.00	Micaceous schist (mica slate)	0·23	Black gabbro	0·10
Liparite pumice stone	0·56	Vesuvius ash (upper layer)	0·19	Pitchstone porphyry	0·09
Rock salt	0·44	Vesuvius ash (middle layer)	0·18	Diabase	0·09
Granulated lime	0·42	Fluxing sand	0·17	Obsidian	0·09
Sandstone	0·38	Anhydrite	0·14	Hekla lava (Spitzbergen)	0·08
Granite	0·36	Syenite	0·13	Clayshale	0·07
Gypsum	0·34	Limestone	0·12	Basalt	0·06
Trachyte	0·30	Biotite gneiss	0·12	Vesuvius lava	0·05
Trass	0·26	Quartz porphyry	0·11	Etna lava	0·05
Clay	0·24	Trachyte lava	0·10	Lignite	0·05

Wilsing and Scheiner's Moon measurements were made with an 80-cm refractor, and the passbands used centred on 448, 480, 513, 584 and 638 mμ. The points selected were (a) in central Mare Imbrium and (b) in the bright region between Macrobius and Proclus, and the normalized reflection coefficients of these regions were given, in the wavelengths mentioned above, together with the normalized reflection coefficients of some terrestrial rocks (see Table 5-2-2).

TABLE 5-2-2

Substance \ λ(mμ)	448	480	513	584	638
Rock salt	62	73	77	87	100
Trass	58	71	82	88	100
Vesuvius ash (middle layer)	50	64	66	88	100
Fluxing sand	54	68	71	95	100
Loam	55	71	84	98	100
Vesuvius lava	65	71	83	94	100
Moon (a)	64	66	65	88	100
Moon (b)	57	59	62	86	100

The tabulated results show that, in general, the substances have higher reflectivities as the red is approached; a result confirmed by Barabasheff, Ezersky, and Fedorets (1959a) and Teifel (1959b). A lava character was suggested for the seas.

Following this work closely in time, Wood (1910a) photographed the Moon in ultraviolet (310–325 mμ), using for this purpose a quartz telescope lens coated with a silver film so as to absorb the visible light and transmit the ultraviolet, and also in yellow light. In addition, he examined many terrestrial substances in the same wavebands. These researches led him to the discovery of a deposit north-east of Herodotus, which he named provisionally "black 31" because it was least reflective in the ultraviolet wavelength 3100 Å. This deposit later became known as "Wood's Spot". The different intensities of the patch in different wavelengths were well shown in the six plates of the Aristarchus region which were given by Wood (1910a). Wood's laboratory results are summarized below, and indicate that "black 31" might be due to the presence of sulphur (Table 5-2-3). Urey (1958) has commented that this sulphur may have been formed by the decomposition of hydrogen sulphide by the action of sunlight, the hydrogen escaping from the Moon.

Other accounts of this work have been given: Wood (1910b; 1910c; 1912b; 1914). In this final report on lunar petrography, Wood (1912a) showed that Wood's Spot could have been due to even a very slight amount of sulphur deposited there: even a slight

TABLE 5-2-3

Sulphur	*ry au*	Calcium carbonate	*ry ru*	Granite	*ay au*
Zinc sulphate	*ry ru*	Lead acetate	*ry ru*	Rhyolite	*ay au*
Kaolin	*ry ru*	Zinc oxide	*ry au*	Powd. quartz	*ry ru*
Talc	*ry ru*	Shale	*ay au*	Granite	*ay au*
Arsenic	*ry ru*	Limestone	*ay ru*	Pitchstone	*ay au*
Sod. carbonate	*ry ru*	Chalk	*ry ru*	Felsite	*ay au*
Powdered glass	*ry ru*	Trachyte	*ay au*	Volc. tuff 1	*ay ru*
Calcium sulphite	*ry ru*	Clay	*ay ru*	Volc. tuff 2	*ay au*
		Augite	*ay au*		

Key: r = reflects, a = absorbs, y = yellow light, u = ultraviolet light.

condensation of a vapour containing sulphur would have been conspicuous in ultraviolet light. He stressed the need for further work over wider ranges of wavelength, with larger apertures and under better conditions than were available to him.

An impressive piece of research was then carried out by Miethe and Seegert (1911a), who worked over a more limited colour range, using the passbands 360–330 mμ (ultraviolet) and 700–600 mμ (orange), but nevertheless found many differences on the Moon's surface. Their method was to superimpose the images of the ultraviolet and orange light dispositives on a screen, after passing the beams through complementary filters; any colour on the screen showed the differences in the photographs. Miethe and Seegert (1911b) used chemical filters in conjunction with a 30 cm, f/6, reflector, modified to f/23·3. Their exposure times for full Moon were 20 sec in orange light and 120 sec in ultraviolet light. A coloured impression of full Moon was given, to illustrate their paper.

Important results were found about the phase-intensity variation of the observed colour. The authors found that the selective absorption was most marked at full Moon, and that the colours were not generally noticeable until one to two days after sunrise at any particular place. The strong green colour of Mare Tranquillitatis was not detected until full Moon, but the red colour of Mare Serenitatis (this mare is greener round the edges) was detected at sunrise. (Pickering (1924b) said that, near first quarter, Mare Frigoris was clearly brownish as compared with the neutral grey of Tranquillitatis: the greener regions are often described as greys by visual observers.) Miethe and Seegert suggested that the fact that the colour was not so marked just after sunrise was due to shadows cast by small unresolvable objects influencing the general albedo, rather than to selective reflections.

A beautiful, coloured impression of full Moon, showing which parts reflect ultraviolet more strongly and which parts reflect more orange light, has been given by Miethe and Seegert (1911c). It deserves close study. It is interesting to notice that the halo around Tycho reflects less ultraviolet light than orange. Many points of difference found by Miethe and Seegert were verified later by W. H. Wright and others.

Taking a different approach, Rosenberg (1921a) noted Götz' earlier measurements of the photographic brightnesses of fifty-five

points, and he, himself, measured the brightnesses of the same points photometrically. He found that when the photographic were subtracted from the visual magnitudes, the residuals (generally of the order of only 0·1 mag.) were positive for S.W. Mare Crisium, S. Mare Foecunditatis, mid Mare Serenitatis, Mare Nubium (near to the Straight Wall), Bessel, S.W. Mare Nectaris, and W. Mare Imbrium, and negative for S. Mare Tranqillitatis, Oceanus Procellarum, Grimaldi, Mare Tranquillitatis (just south of Palus Somnii), Mare Vaporum, E. Oceanus Procellarum, E. Mare Frigoris, and S. Oceanus Procellarum. This means that the first-mentioned group reflect more red light than the second, bluer group of reflectors. The results, although quite crude, confirm the spectrophotometric work of other investigators.

Further spectrophotometric measurements were made by Wilsing and Scheiner (1921b) when they extended their measurements, over a wider range of wavelengths, (451, 472, 494, 514, 535, 556, 577, 593, 615, 642 mμ) to six new points on the Moon's surface, and showed that the brighter parts of the surface reflected more red light than the darker parts. (Their measurements were corrected for atmospheric absorption and for absorption at the objective.)

Barabasheff (1924a) measured the full-Moon intensities of forty-six points photographically, using a 10½-in. reflector, in red (620 mμ), green (500 mμ), and violet (400 mμ) light. The intensities, given with an error of $\leq \pm 0^{m}{\cdot}03$, were corrected for selective absorptions in the Earth's atmosphere and at the telescope mirrors, and the nature of the solar spectrum was taken into account. Comparisons of his brightness estimation of the same points with the photographic observations of Götz and with the visual work of Rosenberg, indicate large differences. It is thus most important in work of this nature to define closely the passband used, the lunar co-ordinates of the point in question, and the Earth–Moon–Sun relationship.

Barabasheff found the colour indices of the forty-six regions which he had examined, and deduced that the marebase materials generally had their maximum brightness in the green, as had also bright regions such as Tycho, Kepler, and Aristarchus. Regions which had, however, greater brightness in red light were Mare Serenitatis, W. Mare Imbrium, the region between Mare Foecunditatis and Tranquillitatis, Plato, Grimaldi, and the part of Oceanus Procellarum between Kepler and Aristarchus.

Many of these results might seem to be in conflict with those sketched above, but this is not so. It is important to note that to compare apparent reflectivities in different wavelengths is not the same as to compare absolute reflectivities: the apparent intensities for the forty-six points were, without exception, greater in *red* light. Examples are given in Table 5-2-4.

Comparisons of these reflectivities with Wilsing's data for terrestrial rocks indicated that basalts, obsidians, lavas and volcanic ashes, were the most probable lunar rocks.

Working at the prime focus of the Lick Crossley Reflector in September 1926, Wright (1929) photographed at intervals of a day or two, between ages 7 days and 22 days, with filters transmitting ultraviolet (c. 360 mμ), violet, green, orange and red (c. 760 mμ). Much of Wood's and Miethe's and Seegert's work was confirmed. Wood's Spot was confirmed to be dark in ultraviolet and was seen to have a "fine complex structure".

In light of wavelength centering on 760 mμ, Wright found large, conspicuous, dark patches in Mare Imbrium, and his photographs showed clearly that the western part of Mare Imbrium was relatively brighter in this wavelength than was the eastern half, especially at phases near to full Moon, and thus confirmed the work of Miethe and Seegert on phase-variation. There were, in the western part of this Sea, small dark patches in ultraviolet. The limb east of Sinus Roris was found to be bright in red light and dark in ultraviolet, especially near to last quarter. This, therefore, is a region which might have the same constituent as Wood's Spot.

Mare Foecunditatis was dark and appeared complex in red light, and the border of Mare Serenitatis was likewise dark in red and not in ultraviolet. Again, western Mare Crisium was generally darker in

TABLE 5-2-4
REFLECTIVITIES IN DIFFERENT WAVELENGTHS

	Apparent			Absolute		
λ(mμ)	400	500	600	400	500	600
Mare Tranquill.	$+0^{m}{\cdot}60$	−1·16	−1·72	−0·10	−0·19	−0·09
Aristarchus	$-0^{m}{\cdot}50$	−2·25	−2·39	−0·27	−0·51	−0·43

red light, as were Grimaldi and Oceanus Procellarum. However, Mare Frigoris was generally lighter in red, like western Mare Imbrium. These are all only apparent differences, of course.

Wright found some interesting patches on the shores of Mare Humorum. Those on the northern shore were faint in ultraviolet and dark in red, whilst those on the southern shore were almost as dark in ultraviolet as they were in red light. All of these things are detectable on Miethe's and Seegert's colour photograph.

An interesting fact which Wright pointed out was that the rays were "uniformly recorded in all colours".

Keenan (1931) used the 36-in. reflector of the Steward Observatory to take photographs in six different spectral regions defined by the mean wavelengths 740 mμ (infrared), 700 mμ (red), 530 mμ (green), 440 mμ (blue), 410 mμ (violet), and 330 mμ (ultraviolet). Working at the Cassegrainian focus (with a consequent focal length of 13·7m), he measured the brightness of thirty-six lunar areas in each of these colours, in terms of the average brightness of the Moon. By comparison with its surroundings, he found that Wood's Spot was 20% brighter in the infrared than in the ultraviolet. Maria often showed green spots, he said.

Some important quantitative work has been done, more recently, by Stair and Johnston (1953a) on full Moon. They used a siderostat with no condensing lens or mirror, and therefore their measurements were on the light integrated by the full lunar surface; they were made when the Moon was at its highest possible altitude above the horizon, to minimize the interposed air mass. A description of their spectro-radiometric equipment has been given by Stair (1951a). Previous work had been done on the Sun (Stair, 1951b; 1952a) and the spectral responses for the Sun (Stair, 1952a) and for the Moon were both manipulated to the respective intensities outside the terrestrial atmosphere and were then plotted together.

A comparison of these curves showed that the reflectivity of the Moon decreased with decrease of wavelength, that there was a selective absorption in the waveband 380–390 mμ, and that there was a sharp decrease of intensity into the ultraviolet which commenced at about 360 mμ.

It should be borne in mind that characteristics such as these would be still more sharply in evidence if this method of analysis were to be applied to restricted regions such as Wood's Spot. Although this

particular part has not yet been studied from this point of view, Vigroux (1956) has used a photographic spectrograph (1952b) to compare $y(\lambda)$, the logarithm of the ratios of the intensities of a given region and the region at the centre of the full Moon, with the mean wavelength used in the determination of these intensities, and the regions which Vigroux selected were Tycho, Mare Imbrium, Mare Tranquillitatis, Mare Serenitatis, Copernicus, Mare Nubium, and Mare Humorum. His curves, extending between 350 mμ and 630 mμ, showed little variation, but there was a tendency for the quantity $y(\lambda)$ to decrease systematically for Tycho at $\lambda < 430$ mμ, for Mare Imbrium at $\lambda < 420$ mμ, for Mare Serenitatis at $\lambda < 490$ mμ, and for Copernicus at $\lambda < 410$ mμ. For Mare Tranquillitatis, $y(\lambda)$ increased systematically as λ decreased, whilst for Maria Nubium and Humorum $y(\lambda)$ remained constant for all values of λ. These observations, as for those of Stair and Johnston, were made with the Moon near to the meridian, so as to minimise variations in air mass.

Further photometric spectrophotometry—this time using a comparison method to eliminate the necessity of colour corrections—was performed by Dubois (1960). Reflectivities of general types of lunar terrain were compared with those of crushed rocks in seventeen wavelengths lying in the range 382-628 mμ. The curve for gneiss which had been heated to red heat fitted the lunar curve best. Heated diorite also fitted fairly well, although not as closely as gneiss. Trachyte yielded a curve which was similar to that of a dark grey area like Mare Crisium. Dubois stressed that the heating was merely one means of diminishing the albedos of the rock samples; on the Moon, other mechanisms may have produced similar effects.

Taking into account other known physical properties of the lunar rocks, Stair and Johnston (1953a) deduced that a surface having a yellowish, glass-like composition could possibly be responsible for all the observed phenomena. They found that certain silica glasses, described previously by Stair (1948) had a cut-off corresponding with that observed for the Moon. "A small iron content would result in selective absorption at 380 to 390 mμ and would give the material a slightly yellowish color." A powdered surface of such a glass would also be consistent, according to Stair and Johnston (1953a) with the observed temperatures, and with albedo and polarization measurements.

There is an indirect way of ascertaining the shade of the lunar rocks: this is via their polarizing properties. The Carnegie Institution Moon Committee, under the chairmanship of F. E. Wright (1927; 1930), determined that the polarization of moonbeams never exceeded 15–25%, whereas that in light reflected by basic and dark rocks such as basalts, serpentines, and so on, the polarization sometimes exceeded 95%. The polarization of moonlight was approximately equal to that of light reflected by pumices, quartz porphyries, powders of transparent substances, and, possibly, trachytes and granites. Hence, the Committee concluded that the lunar materials were light coloured like pumice, granite, or sandstone, and not dark like basalt.

No mention has yet been made of any deep infrared work. The problem is complicated by absorptions in the Earth's atmosphere. However, Coblentz (1905) investigated the infrared reflection spectra of many polished silicates and his results are set out very plainly in graphical form. Coblentz compared his graphs with Langley's (1888) results for the Moon and wrote, "One can readily see from these curves that a reflecting surface composed of rocks like granite, basalt, diorite, etc., which are mixtures of feldspar, hornblende and mica, would give a curve similar to that of the Moon."

To detect any one type of mineral in this way would hardly be possible, because so many rocks have similar infrared reflection spectra, but, used in conjunction with other wavelengths, the deep infrared might prove to be of use: *all* possible frequencies must be employed if we are to attempt to track down the exact nature of the lunar rocks.

5-3. Summary

In conclusion, the following points might be noted:

1. Colours are very difficult to see with the naked eye, but colour *differences* can be detected with the naked eye and are most marked in maria.
2. The colours of a particular spot vary apparently with time, and this variation might be due to shadows.
3. The continents reflect more red light than the seas, but the absolute reflectivities of the lunar rocks are generally greatest in green light.
4. The rays appear to reflect light of all wavelengths.

5. The overall surface of the Moon absorbs in the waveband 380–390 mμ, and again in the ultraviolet, commencing at about 360 mμ. Certain spots absorb ultraviolet light strongly.

The following suggestions, based upon colour work, have been given for the composition of the Moon's surface:

Coblentz (1905)	Granite, basalt, diorite, (mixtures of feldspar, hornblende and mica).
Wilsing and Scheiner (1909)	Maria behave not too unlike lava.
Wood (1910a: 1912a)	Sulphur present in the ultraviolet dark spots.
Barabasheff (1924a)	Basalts, obsidians, lavas, and volcanic ashes.
Wright, F. E. (1927; 1930)	Light-coloured rocks, such as pumices, quartz porphyries, powders of transparent substances, trachytes, and granites.
Stair and Johnston (1953a)	Powdered silica glasses; small iron content.
Dubois (1960)	Darkened gneiss, diorite. Trachyte (dark-grey areas).

Meteorites should be investigated more fully, in comparison with the Moon.

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CHAPTER 6

On the Polarization of the Light Reflected by the Moon

6-1. Work accomplished with purely optical polarimeters

Secchi (1859) stated "I . . . have been surprised to see the enormous difference between (the polarization of) the mountains and the seas. The maximum polarization of the moon is at the seventh day of her age. The full moon is not at all polarized."

Secchi had discovered the now well-known phenomenon of the small amounts of polarization of the lunar continents as compared with the amounts of polarization of the seas and the bottoms of some craters. Although he used only crude equipment, his results have proved to be generally correct.

More than sixty years before Lyot, Secchi (1860a) deduced that the polarization from maria was almost exactly the same for "any inclination of the plane touching the reflecting surface", although Mare Serenitatis polarized slightly more strongly than other maria. In another paper, Secchi (1860b) enlarged on his previous conclusions. He found that the amount of polarization "in the first quarter" was, at any given time, almost the same at all points of similar albedo on the illuminated disk, although there was a slight difference close to the terminator. The plane of polarization was "that of reflection", and the maximum percentage of polarized light during first quarter occurred between ages 6 and 7 days. That Secchi realised that a comparison of the amounts of polarization of moonlight with those of various laboratory specimens would yield evidence of the nature of the Moon's surface, is evident from his statement, "the only thing which practically gives the same result is the glass paper used in the arts".

The object of Parsons' (1878) search was to determine where the polarization of a point of the lunar surface attained a maximum. "It might be possible", he wrote, "to obtain an approximate value

of the refractive index of the material composing that surface, and so to distinguish between a material of a vitreous nature, ejected from volcanoes, and a surface of ice and snow." Evidently he had in mind the application of Brewster's Law, which states $n = \tan i$, where n is the refractive index and i is the angle of incidence which corresponds with an observed maximum in the proportion of polarization. The application is not justifiable (see below).

Parsons knew that Arago (1811) had found the maximum amount of polarization of the integrated light of the Moon to occur at, or near, quadrature, and provisional results given by Parsons for a restricted region—Mare Crisium—confirmed that when the phase angle of the Moon lay between 90° and 100°, the proportion of light polarized in the plane Sun–Moon–Earth (hereafter described as the plane of diffusion) was greatest. His results have been transformed into convenient forms and are given in Table 6-1-1, where ϕ is the phase angle and P is the proportion of light which is polarized, defined as the ratio

$$P = \frac{I_1 - I_2}{I_1 + I_2}, \qquad (6\text{-}1\text{-}1)$$

where I_1 is the intensity of the light which is polarized in the plane of diffusion and I_2 is the intensity of that which is polarized in a perpendicular plane.

Estimations were made for other regions, and Parsons found that the polarization varied with the place chosen "being in general greater on the plains than on the more uneven parts".

Using a Cornu photopolarimeter, Landerer (1889) observed the maria at all nights between phase angles 100° and 140° (for both first and last quarters) and found that more light was polarized during the last quarter than during the first quarter. He suggested that this difference was due to the differing *areas* of the seas in the two hemispheres rather than to any constitutional differences between the individual seas. Later, Landerer (1910) stressed that, in order to get a general result for the angle of polarization of the materials composing the seas, *large* areas of lunabase must be studied. 21% of the light was found to be the maximum amount polarized in the waxing phase, and 33% in the waning phase. These both corresponded to an angle of polarization of 33° 17′ ± 7′, according to Landerer.

TABLE 6-1-1

ϕ (degrees)	30	40	50	60	70	80	90	100	110	120
P (per cent)	1·0	1·5	3·6	5·8	8·7	10·5	11·1	11·1	9·9	9·3

Landerer (1890) also determined the angles of polarization of twenty igneous rock specimens, for plane polished surfaces, his errors never exceeding ±5′. Basalt had a polarization angle of 31° 43′; granite, 32° 20′; and vitrophyre, 33° 18′. "Only vitrophyre," he wrote, "gives an angle of polarization similar to that of the . . . Moon," and he concluded that the Moon's seas must be composed of vitrophyre, a black rock containing crystals of sanidine, magnetite, and hornblende, or some similar acidic rock. This conclusion has been criticized by Salet and by Barabasheff (see below).

Salet (1922) remarked that Landerer always observed the middle of the Moon's crescent: that is, the point at which the angle of incidence of light is equal to the angle of diffusion (the angle between the normal to the Moon's surface, at the point in question, and the direction of the observer): and that other workers (Arago; Secchi) had found large differences in the polarizations of different regions. Landerer's measurements were performed irrespective of the topography, and, hence, were not to be used in arriving at the polarization angle. Furthermore, Salet had done some work on terrestrial substances and had found vast differences in the polarization angles of a given substance when polished and when matt. Parsons' (1878) and Landerer's (1890) suggestions for identifying the material of the Moon's surface could not, therefore, be entertained.

Lyot (1924) plotted the proportion of light polarized against the angle of vision (defined as the angle Sun—point on Moon—Earth), for twenty-three different regions which varied in shade from the dark Sinus Aestuum to the bright spot south-east of Furnerius. He used the polariscope which he had described earlier: Lyot (1923). Curves for all of these regions were similar, but the darker the region the more was the polarization, which varied from 4·5% maximum to 18% maximum. Lyot found also that the proportion of the light polarized increased as the terminator was approached.

In general, the plane of polarization was in the plane of diffusion (defined above) and Lyot called this "positive polarization". He

discovered that, just before full Moon, between phase angles 24° and 0°, the plane of polarization was perpendicular to the plane of diffusion, and he called this "negative polarization". This negative polarization had its maximum of 1·15% for the continents, and 1·35% for maria, at the same angles of vision of about 10° 30′.

Lyot also gave curves for the integrated surface for both a waxing Moon and a waning Moon. These showed the generally larger polarization produced by the waning phases (reaching 8·8% at phase angle 105° as against 6·7% at 95° for the waxing Moon) and that, after maximum at 105° (i.e., during last quarter), there was a sharp cut-off of the amount of polarization "due . . . to the terminator's cutting across the darker Oceanus Procellarum". Lyot pointed out that the measured points were dispersed by libratory effects (the measurements extending over more than one lunation).

Barabasheff (1927a) observed parts of the Moon's surface of 4′ angular diameter. "From the polarization curves of the seas, it follows," he wrote, "that the maximum polarization lies between the polarization angles 33° 57′ and 37° 11′. It is clear that the maximum is rather flattened and, therefore, that it is impossible to estimate the polarization angle more accurately than to one degree." Barabasheff went on to say that Landerer's value of 33° 18′ was therefore unreliable and that Landerer's identification of the crust with vitrophyre was, as a consequence, also unreliable. Landerer had, moreover, investigated specimens with polished surfaces, which differed markedly in nature from the surface of the Moon: again, Landerer's identification could not be correct.

Laboratory experiments showed that materials of larger grain sizes polarized less strongly than those of smaller grain sizes* and that the maximum percentage polarization occurred for smaller angles of polarization in the coarser materials. For a fine powder, however, the polarization was generally smaller than for a coarser powder.* Barabasheff found that a non-polished, absorbent surface showed only a small maximum percentage polarization and, thus, he wrote "the flattended maximum of the Moon's polarization curve is due simply to the roughness of the surface".

"The difficulty remains," he concluded, "that the positions of the maxima of the polarization curves for rough substances cannot be obtained with sufficient precision", and he proposed that it was much

* A result confirmed by Wright (1927b).

better to select rocks which had polarization curves matching the Moon's curve for all values of the polarization angle. Following this method, he found that the polarization curve which corresponded best with the brighter parts of the Moon was that of a brownish-yellow sand. The substance corresponding best with the darker parts of the Moon was a porous type of lava, and the very darkest patches might well have been constituted of obsidian or pumice.

Wright (1927d; 1934a) has described his polarization photometers and has compared his later instrument with Lyot's (1929b). The application of this instrument has been described by Wright (1927b; 1929a) and he found that the polarization of moonlight was at no time greater than 15–25%. "At new Moon* and at full Moon practically none of the light is polarized; the greatest amount of polarization is obtained at the end of the first and third quarters of the Moon."

Measurements were made on laboratory specimens, curves being given for a crown glass, a flint glass, and various basalts. Many other basic rocks were found to give similar curves. For glasses, polished and ground, the polarization decreased as the surfaces became rougher, but the angle of incidence for maximum polarization did not vary much for a given glass. "For basalt *powders* of different degrees of fineness, the amount of polarization falls off with the degree of fineness" (a similar result was found also by Barabasheff, 1927a) "but even for powders finer than 200 mesh the polarization effects exceed those produced by the Moon."

Iron meteorites polarized strongly. "Pumice, powders of transparent substances such as glasses, salts, marble, sulphur, yield low polarization angles like those observed on the Moon. Granites, sandstones and similar rocks show . . . angles appreciably greater than those observed on the Moon. But in powder form, these angles are smaller and of the right order of magnitude." Wright (1927b) also pointed out the following criterion: "It is characteristic of many powder preparations that the polarization angle increases relatively as the angle of incidence increases up to 75° and over. This characteristic may aid us in determining how much of the Moon's surface material is in the form of fine powder."

Extending his previous work, Lyot (1929b) investigated the problem very thoroughly. His reasons for doing so were twofold. The

* Presumably this is to be interpreted as meaning a very narrow crescent.

results would contribute to a better understanding of the nature of the Moon and, secondly, it would be essential to know in some detail how the Moon's polarization curves behaved before useful comparisons could be made with the curves for the planets.

Most commonly, Lyot used a lunar image of diameter < 4 mm, but between phase angles 150–160°, when the crescent was very narrow, a different instrument was employed, producing an image 16 cm in diameter. In the latter case, the maximum width of the crescent was again only a few millimetres. The eclipse of 1925, 8 February, was utilized for measurements when the Moon was nearly full.

Lyot's results may be divided into two sections; the first giving the relationship between the phase angle and the proportion of the integrated light which was polarized, and the second relating his conclusions which were drawn from a regional study.

The results of the first of these sections have been given graphically (see Fig. 6-1-1). The difference in the polarizations of the waxing and the waning Moon was due to the fact that the seas occupied an area twice as large in the second and third quadrants as in the first and fourth quadrants of the Moon. The sharp cut off which appeared during last quarter was due to the terminator having cut across the dark seas Imbrium and Nubium. At phase angles 0–35° and 150–180°, the curves for the waxing and the waning moon united. At phase

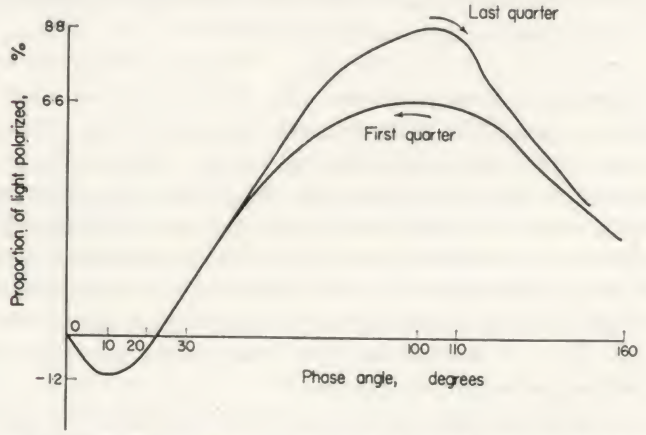

FIG. 6-1-1. Variation of the proportion of light polarized by the Moon with the phase angle, for both a waxing and a waning Moon: Lyot (1929)

angle 23° 30′ the polarization became zero and reappeared a few hours nearer full, in a perpendicular plane. The phase angle at which this phenomenon occurs is called the "inversion angle". The maximum negative polarization was 1·2%. This occurred at phase angle 11°, and annulled when the phase angle reached 0°. This behaviour was symmetrical about full Moon.

From his regional study, Lyot drew the following interesting results. The *plane* of polarization at a given phase was found to be constant for *any* point on the surface. (The accuracy of these results was generally less for the continents than for the seas, because of the generally smaller percentage polarization produced by the continents.) Thus, the plane of polarization, always either parallel or perpendicular to the plane of diffusion, did not depend upon the orientation of the lunar surface with respect to either the direction of illumination or the line of sight, but only upon the phase angle. The *proportion* of polarized light seemed to vary inversely with the albedo. For the brightest regions, the amount did not exceed 4·8%; for the continents the maxima lay between 6·5% and 7·5% and were thus fairly constant in comparison with the maxima for the seas, which had maxima that varied very irregularly, from one point to another, between about 12% and 16%. It is interesting to compare these figures with Parsons' (1878) maximum of 11·1% for Mare Crisium. Because of this variation, Lyot stressed that it was important to specify the co-ordinates of any point in question.

There are, however, no systematic differences, at a given time, in the proportions of light polarized by the same type of topography occupying different positions on the Moon, except for a generally greater proportion in the neighbourhood of the terminator—(results mentioned by Secchi in 1860)—and, possibly, a very slight difference along a line of selenocentric latitude, due to the real small change in the angle of vision. This difference near to the terminator was noticeable even as far as 10° (selenocentric) away, and increased rapidly up to the actual terminator. Lyot concluded "the polarization is independent of the angle which the surface makes with the line of sight", and he said that the proportion of light which was polarized depended only upon the angle of illumination in the neighbourhood of the terminator, where the Sun's elevation was small.

The inversion angle was found to vary slightly (by about 1°) for different regions. Thus, the first region to show no polarization near

to the general inversion angle was that around Tycho, and the last was the extensive region east of Kepler.

Outstanding results of the researches of members of the Carnegie Institution Moon Committee have been reported by Wright (1927c; 1930; 1934b; 1935b; 1936b; 1937; 1938). Any rock may have been present on the Moon in which internal reflections occurred and depolarized the reflected light. Such rocks were pumices, volcanic ashes, quartz porphyries, powders of transparent substances, and, possibly, trachytes and granites. The changes in the amount of polarization for different angles proved that the surface was rough, and not smooth.

The Committee investigated the phenomenon of negative polarization and found that it did not exceed about 1% during the three-day period of its appearance. Wright (1934b) wrote, "it is exceedingly interesting theoretically, because the plane of vibration is in the plane of incidence rather than the normal thereto; the change is probably due to diffraction".

The Committee determined the maximum percentage of polarization for each of twenty-four regions at different phases. Work was also done on terrestrial substances (1935b; 1936a) and it was found that the amount of polarization introduced on reflection from non-polished surfaces depended upon (a) the chemical nature of the material; (b) the physical nature of its surface; (c) the direction of illumination; (d) the direction of observation; (e) the phase angle. It was found (1936b) that in rough, non-polished materials, the polarization was due chiefly to diffraction and scattering, and only in small part to reflection. Negative polarization was also observed in terrestrial materials, and was due to diffraction rather than to reflection.

Graphs relating the percentage of plane polarization to the phase angle for different maria, and for various mountainous areas, have been presented by Wright (1935a). Maxima occurred at phase angles 100–110° and 280–290°, and were 16% for one or two maria. These results were in very good agreement with Lyot's. The maximum difference in the peak polarizations due to maria appeared to be ~6%, and, due to the mountains, only ~3%. (The corresponding figures given by Lyot were ~4% and ~1%.) The peaks relating to the mountains seemed to occur nearer to the Moon's quarters (phase angles 90° and 270°) than did the peaks which related to the seas. At

phase angles ±22–23° the polarization was found to be zero for practically all points, in confirmation of Lyot's work. It was also zero at 0° (full Moon) and 180° (new Moon).

Visual measurements on the earthlit portion of the Moon with a polarimeter attached to the coronograph at the Pic-du-Midi were made by Lyot and Dollfus (1949). Strong polarization was found, peaking at a phase angle of ~80° when it exceeded 10% for the seas and was 1·2 times stronger on the seas than on the continents. These observations were made between phase angles 38° and 115° and the plane of polarization was always parallel to the plane of diffusion. The authors explained ". . . the earthlight will be polarized strongly, but diffusion of it at the lunar surface will depolarize it, it being multiplied by a coefficient of depolarization (~0·3) which varies inversely as the albedo, as for volcanic ashes". For phase angles less than 35°, it was no longer possible to make visual measurements, since the light diffused by the Earth's atmosphere was no longer negligible. However, photographic measurements could be made with the coronograph "less than 38 hr before or after full Moon".

Dollfus (1952) plotted the albedos of volcanic ashes and the Moon against their respective coefficients of depolarization. "These absorbent spherules (of volcanic ashes) have a coefficient (of depolarization) which varies very regularly with their albedos," he wrote. Dollfus concluded, "the measurements confirm the pulverized, absorbent nature of the lunar surface materials". In a previous paper, Dollfus and Cailleux (1950) had shown from a study of the polarization curves of sands and quartz limestones that these substances were not present in appreciable quantities on the Moon.

Dollfus (1956a) continued his investigations by making an extensive comparison of the Moon's polarizing properties with those of terrestrial substances. His results relate the proportion of polarized light coming from solid, composite materials, with vitreous and with diffusing surfaces, and coming from various pulverized substances, some described as being slightly absorbent and others as being opaque, to (a) the phase angle; (b) the "lateral inclination" (the angle between the surface normal and the line of sight, measured in a plane which is perpendicular to the plane of diffusion); and (c) the angle of diffusion (measured between the surface normal and the line of sight, in the plane of diffusion). Many materials showed negative polarizations at phase angles of less than 15°. Dollfus has

also given several graphs which relate the proportion of polarized light in the direction of illumination to the inclination of the surface. Results have also been given for sands, silica-muds, natural clouds, and the Earth's atmosphere. Studies of the ashen light confirmed the pulverized nature of the lunar rocks, and comparison with terrestrial materials led Dollfus (1957) to conclude that the structure of the rocks was similar to that of black, opaque granules.

6-2. Photoelectric polarimetry

Öhman (1945) has probably been the first to investigate the Moon's polarizing properties by the use of a photoelectric detector. His instrument provided a great improvement over previous methods: applying it to the Moon, Öhman could measure a proportion of polarization of 2 parts in 10,000 parts. For a point near to Bessel he found an inversion angle of 21° 48′ (compare Lyot's value of 23° 30′) and noted that his curve of the degree of polarization versus phase angle agreed well with Lyot's curves.

In a discussion with Wlérick (1956b), who had designed an equally sensitive instrument for solar work, it was agreed that, for future work on the Moon, visual polarimeters would be better suited to investigations of large areas, but photoelectric polarimeters would be of great importance in the study of very restricted areas of the Moon's surface. Öhman has predicted that an interesting field for future research might be to measure the polarization of lunar formations with photo-tubes of different spectral sensitivities.

6-3. Summary

In general, maria polarize more light than do the continents. Also, when specific small areas are considered, it is found that the proportion of polarized light depends on the albedo, assuming maximum amounts of ~5% for the brightest areas and ~20% for the darkest areas. However, for country of given albedo, the proportion of polarized light coming from it at a given time is independant of its position on the Moon's disk, except for points close to the terminator.

Considering the whole of the illuminated surface of the Moon at different times, it emerges that the amount of polarization is greatest at the first and last quarters (more so at the last quarter because of the larger proportion of dark maria available for scattering the light).

No light is polarized at full Moon, and practically none is polarized when the Moon is a very narrow crescent.

The plane of polarization lies in the plane Sun–Moon–Earth, except for phase angles between about −24° and +24° (near to full Moon) when the plane of polarization turns through a right-angle; in this new plane, the maximum proportion of polarized light is only ~1%.

A general inference which may be drawn from these results by the use of laboratory models is that, considered in detail, the Moon's surface is very rough. By comparison of the lunar polarization curves with those representing the behaviour of terrestrial specimens, the following suggestions have been made of the composition of the Moon:

Barabasheff (1927a)	*continents*: brownish-yellow sand *maria*: porous lava
Wright (1927b; 1929a)	pumice, powders of transparent substances (glasses, salts, marble, sulphur), powdered granite or sandstone.
Dollfus (1952)	pulverized, light-absorbent materials, with a structure like that of black, opaque granules.

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CHAPTER 7

On the Temperature of the Moon

7-1. Surface temperatures from Stefan's law

A body in thermal equilibrium radiates the same amount of energy as it receives. If it is supposed that the Moon acts like a black body in thermal equilibrium, its temperature may be computed from Stefan's law,

$$E = \sigma.\theta^4, \tag{7-1-1}$$

where E is the total amount of radiant energy emitted by a unit of area of the heated Moon in unit time, θ is the absolute temperature of the same part of the Moon's surface, and σ is Stefan's constant. The result must refer to the highest possible temperature attainable for a given distance of the Moon from the Sun since, in practice, some energy would be absorbed and would flow into the interior of the Moon and some would be reflected.

Let the point on the Moon at which the Sun is vertically overhead be at a distance r from the Sun. In unit time, the amount of solar energy crossing the sphere of radius r is $4\pi r^2 E$. By definition of the solar constant, S, and by the principle of the conservation of energy, this must be equal to $4\pi r_0^2 \,.\, S$, where r_0 is one astronomical unit. Thus,

$$E = \left(\frac{r_0}{r}\right)^2 .S. \tag{7-1-2}$$

From equations (7-1-1) and (7-1-2),

$$\theta = \left(\frac{r_0}{r}\right)^{\frac{1}{2}} \left(\frac{S}{\sigma}\right)^{\frac{1}{4}}. \tag{7-1-3}$$

Taking the quantities $S = 1{\cdot}374 \times 10^6$ erg cm^2 sec^{-1}; $\sigma = 5{\cdot}67 \times 10^{-5}$ erg cm^{-2} sec^{-1} deg^{-4} from Allen (1955a) it follows that, with $r = r_0$, $\theta \approx 394°{\cdot}5\text{K} = 121°{\cdot}5\text{C}$. Varying r between its possible limits (due to the eccentricity of both the Earth's and the Moon's orbit)

shows that the temperature may vary, because of this, through a few degrees. Thus we see that the upper limit of the temperature of the Moon's surface due to solar heating is at present around 122°C. There are, of course, some uncertainties in the values of the constants adopted.

Poynting (1904) applied this method to the Moon and found $\theta = 426$°K (153°C), but his value of S was too large. It will be seen (7-3) that the measured surface-temperatures, although based on the fourth-power law, are less than the computed black-body temperatures.

7-2. The measurement of surface heat changes

Langley (1884a) summarized Lord Rosse's observations of the heat flux of the Moon and experimented with bolometers. At this time, astronomers were uncertain as to whether they could detect any heat emitted by the Moon. Langley concluded that the Moon *did* radiate planetary heat (that is, it emitted solar heat, after absorbing some radiation, as well as *reflecting* solar radiation), but the exact amount of the planetary heat was not known. By comparing the Moon's heat with that coming from a Leslie Cube filled with boiling water, he was able to suggest that the temperature of the Moon was somewhat below 100°C. These very tentative conclusions, arising from lengthy discussions of the problem, do not overemphasize the difficulties which confronted the pioneers in this field of research.

Using a very small telescope (focal length 1m), Boeddicker (1884b) reflected the Moon's heat by means of two small concave mirrors upon two thermopiles, alternately, exposing each thermopile for one minute at a time. These were wired to a mirror galvanometer and the deflections were plotted against time during the total eclipse of 4 October, 1884. The heat had returned almost to its original flux at the last contact of the penumbra, which occurred 120 min. after the end of the total phase. Boeddicker found that he could not measure any heat coming from the totally eclipsed Moon, because his instruments were not sensitive enough, but he wrote "a few observations obtained before the total phase began show plainly that the minimum of the radiated heat takes place later than that of the Moon's light".

Langley and Very (1889) scanned an image of the Moon in the infrared, with a spectroscope having rock salt components, and, with

a bolometer, they claimed to have detected heat coming from the umbra of an eclipse. The amount of energy flowing from the Moon in unit time was found to vary with the wavelength. The wavelength corresponding to the maximum rate of flow of energy is characteristic of the temperature of the Moon, this wavelength being displaced towards the longwave end of the spectrum as the temperature decreases, in accordance with the law discovered by Wien. They applied Wien's displacement law to conclude that the *mean* temperature of the sunlit portion of the Moon was probably not greatly in excess of 0°C. There was necessarily much uncertainty to be attached to this result, because of atmospheric absorptions and the flattened nature of the curve, although an attempt to allow for absorptions in the Earth's atmosphere was made by observing when the Moon was high, and then low, in the sky. The zero point on their arbitrary temperature scale was estimated by pointing the bolometer into space, adjacent to the Moon. Comparison measurements were made on the heat reflected from the blackened surface of a Leslie Cube at −10°C. Langley and Very maintained that the absorption bands in the Earth's atmosphere varied in width, and even in position, from night to night.

A few years later, Very (1898) published the results of his measurements of the radiative properties of some laboratory substances but was not able to demonstrate that these had any important bearing on the temperature range of the Moon. Coblentz (1906) examined in the laboratory many of the chief constituents of the Earth's crust (especially silicates) and found bands of metallic reflection from 8·5 μ to 10 μ. He suggested that the Moon's surface was similarly composed and that "... it is just as reasonable to consider the radiation from the Moon at 8·5 μ to 10 μ to be reflected from the Sun as to consider it due to a temporary rise in temperature of the sunward side of the lunar surface ...".

Again, Coblentz (1907) compared Langley's heat curves for the Moon with the selective reflection curves from silicates in the region transmitted by the Earth's atmosphere (8–12 μ) and maintained that the Earth and the Moon could be considered as selective reflectors with bands of metallic reflection from 8·5 μ to 10 μ. On this assumption, the Moon would reflect only 3–5% of the Sun's radiation in the region 4–7 μ, and <1% at 7 μ, but it would reflect as much as 50–80% of the incident radiation in the band 8–10 μ and, hence, very low

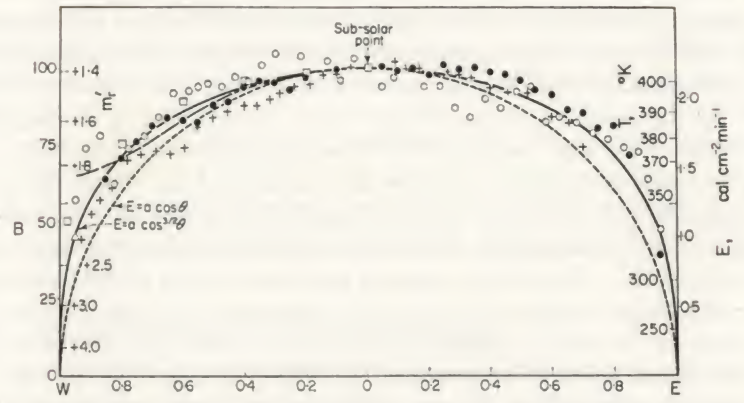

FIG. 7-2-1. Distribution of planetary heat across the disk of a full Moon: Pettit and Nicholson (1930). (The abscissa is calibrated in units of the Moon's radius.) (*Astrophysical Journal*)

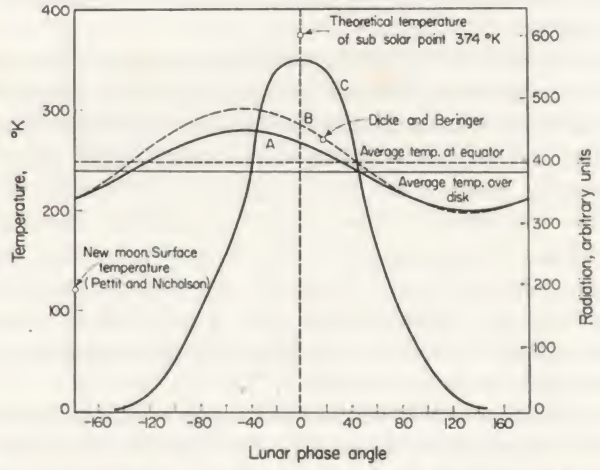

FIG. 7-2-2. Variation of the temperature of different parts of the Moon with the phase angle: (A) average temperatures, as measured at λ = 1·25 cm by Piddington and Minnett (1949); (B) temperatures in the central regions of the disk, as measured at λ = 1·25 cm by Dicke and Beringer; (C) average *surface* temperatures, as measured in the range λ = 8-14μ by Pettit (1940). (*Australian J. of Scientific Research* A)

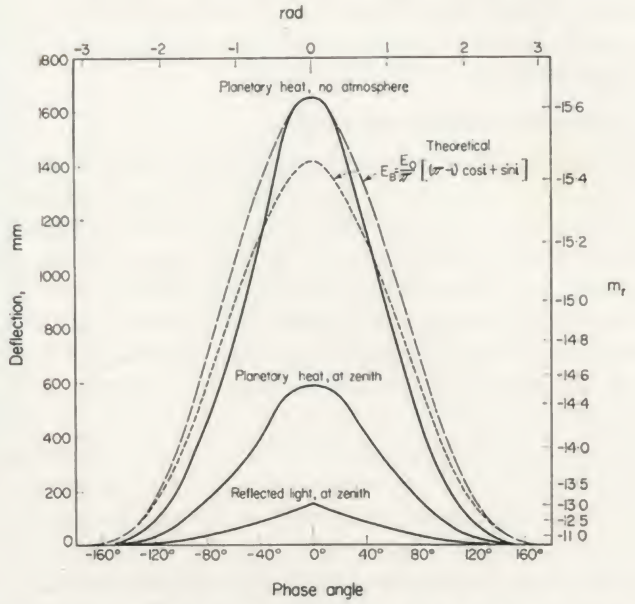

FIG. 7-2-3. Variation of the planetary heat of the Moon with phase angle: Pettit (1945). (A deflection of 303 mm = 10^{-5}cal.cm^{-2}.min^{-1}.) (*Astrophysical Journal*)

temperatures would be associated with the Moon's sunlit face. Coblentz' assumption that the Moon's surface possessed these properties seemed reasonable enough until Pettit and Nicholson (1930) showed that the assumption was incorrect (see 10-4). The apparent heat distribution across the disk of full Moon was measured by Pettit and Nicholson (1930) with the apparatus described below (7-3). Their curve has been reproduced in Fig. 7-2-1.

Proportional values of the total heat coming from the Moon at different phases were plotted by Parsons (1873). Using a telescope only 6·4 cm in aperture, yielding an image of the Moon never greater than 0·87 mm, Pettit (1935) again examined the integrated heat and light from the Moon at different phases (see Fig. 7-2-2). The planetary heat was separated from the reflected sunlight by a microscope cover glass (see below) and the apparatus was calibrated with a standard source. Pettit reduced his observations to no atmosphere at the mean distance of the Sun and Moon from the Earth. At the suggestion

of Russell, Pettit (1945) revised the previous result for the radiometric magnitude m_r (see below) of the planetary heat from full Moon and obtained −15·6 (Fig. 7-2-3).

7-3. Measured surface temperatures

The measurement of planetary temperatures was put on a firmer basis than ever before when Pettit and Nicholson published their important results. Their equipment (see Pettit and Nicholson, 1922) was painstakingly developed so as to have the maximum possible sensitivity at that time, and was carefully stabilized so as to minimize effects produced by local disturbances. The special vacuum thermocouple (Fig. 7-3-1) was clamped to the plateholder at the Newtonian focus of the Mount Wilson 100-in. reflector, and was wired to a galvanometer of current sensitivity 3×10^{-10} amp mm^{-1} at 8 m scale distance. Deflections were recorded on a moving photographic plate which was placed variously at 6–10 m from the galvanometer.

In order to calibrate the equipment, Pettit and Nicholson (1928) defined the "radiometric magnitude", m_r, of a star, as that apparent magnitude of an A0 star which would give the same deflection of the galvanometer. Between the years 1922 and 1927, many stars were observed with a vacuum thermocouple which had a rock-salt window and junctions of bismuth and bismuth-tin alloy. It was found from laboratory measurements of the radiation from standard lamps that a source of radiometric magnitude m_r had an energy output

$$E = 17{\cdot}3 \times 10^{-12} \times 2{\cdot}5^{-m_r} \text{ cal cm}^{-2} \text{ min}^{-1},$$

this being the rate of receipt of energy by the thermocouple from each exposed square centimetre of the concave mirror of the telescope. It follows from this equation that

$$\log_{10} E = -10{\cdot}762 - 0{\cdot}4\, m_r.$$

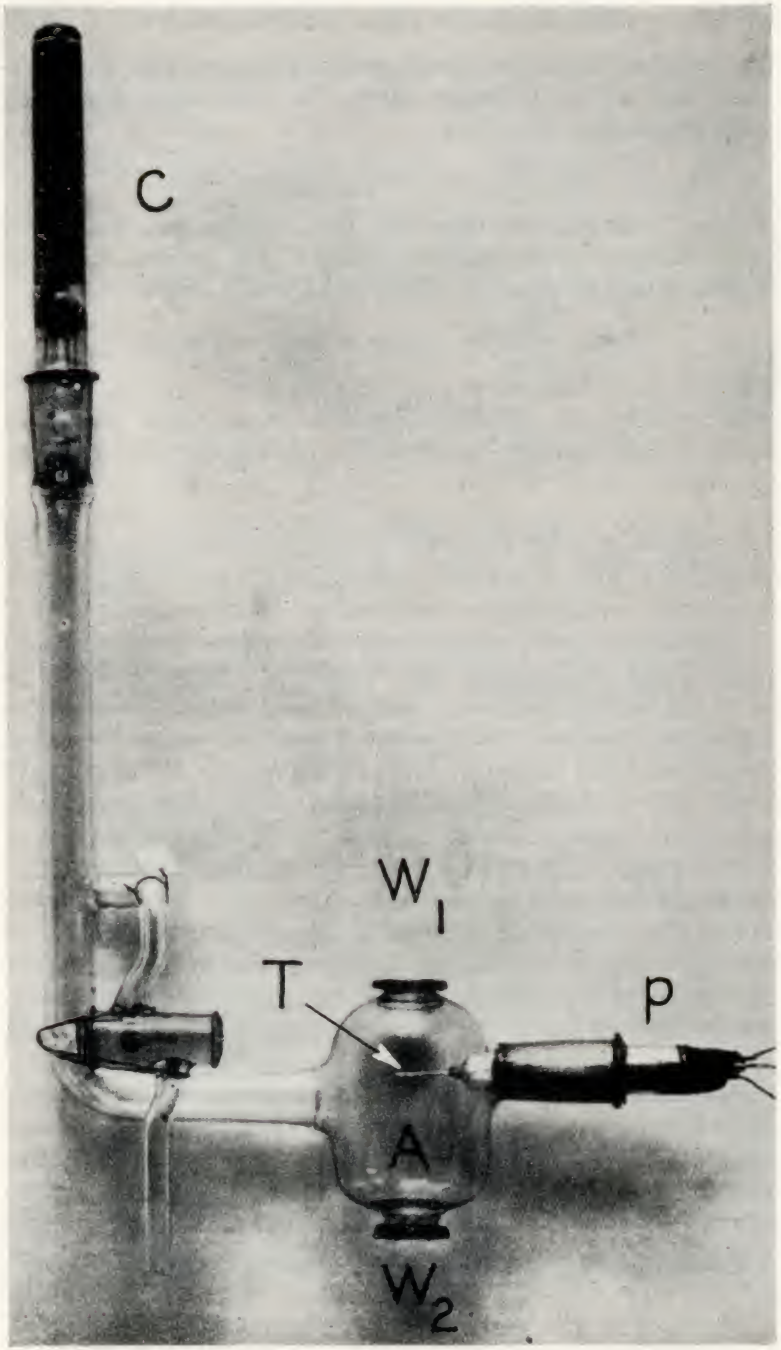

FIG. 7-3-1. Vacuum thermocouple used by Pettit and Nicholson for the measurement of lunar temperatures (1922). The cell A—the body of the instrument—has an inner diameter of 4·2 cm and Pyrex walls 1·5 mm thick. C is a quartz tube containing metallic calcium (held in place by a wad of glass wool). P is a glass plug containing three platinum wires, to which are attached two thermocouples at T. W_1 is the quartz window, 1·5 mm thick, which admits the radiation, and W_2 is a glass window, 1·28 mm thick, which allows the observer to view the thermocouple junction against the image of the Moon (*Astrophysical Journal*)

This expression for E was then corrected for absorptions in the atmosphere and at the telescope mirrors by introducing a quantity Δm_r magnitudes, and writing

$$\log_{10} E' = -10{\cdot}762 - 0{\cdot}4(m_r - \Delta m_r),$$

where E′ is the corrected value of E. From this formula, an empirical relationship for the absolute temperature, $\theta°$, of a star was determined experimentally by assuming, in the first instance, that $E' \propto \theta^4$:

$$\log_{10} \theta = 2{\cdot}638 - 0{\cdot}1(m_r - \Delta m_r) - \tfrac{1}{2}\log_{10} d,$$

where d is the diameter of a star in seconds of arc. For a planet differing from a star in that the receiver would "look at" only a fraction of the planetary disk, Pettit and Nicholson (1930) found that they could write

$$\log_{10} \theta = 2{\cdot}612 - 0{\cdot}1(\overline{m}_r - \Delta m_r), \qquad (7\text{-}3\text{-}1)$$

where $\overline{m}_r$ is the radiometric magnitude of the source of planetary heat which is contained by a solid angle of one square second of arc.

When taking measurements on the Moon, the receiver was pointed at the Moon and then at a point in space adjacent to the Moon so as to test for free radiation. Again using the 100-in. telescope, and employing Arcturus and Vega as comparison stars, Pettit and Nicholson (1930) observed a point on the Moon's disk near to the south limb during the eclipse of 14 June 1927. Their deflections, reduced to zenith, indicated that the temperature at the point in question was 342°K (+69°C), and fell to about 180°K (−93°C) during the first partial phase. Then, during totality, there was a slow fall to 156°K (−117°C). For the next few minutes, at the end of totality, there was no change. Then there was an abrupt rise, in 20 min., to the original value of 342°K (see Fig. 7-3-2). The temperature of the dark side of the Moon, measured at a point near to the east limb, was found to be in the neighbourhood of 120°K (−153°C).

As outlined above, the problem would seem to be relatively simple, but it is actually most complicated, as one has to distinguish between reflected and emitted heat and then measure the appropriate component (the emitted heat). The atmosphere of the Earth is a very effective absorber of radiation in certain wavebands, and this further complicates the problem. Pettit and Nicholson (1930) gave the curves of Fig. 7-3-3 for the transmissions of the atmosphere, for the

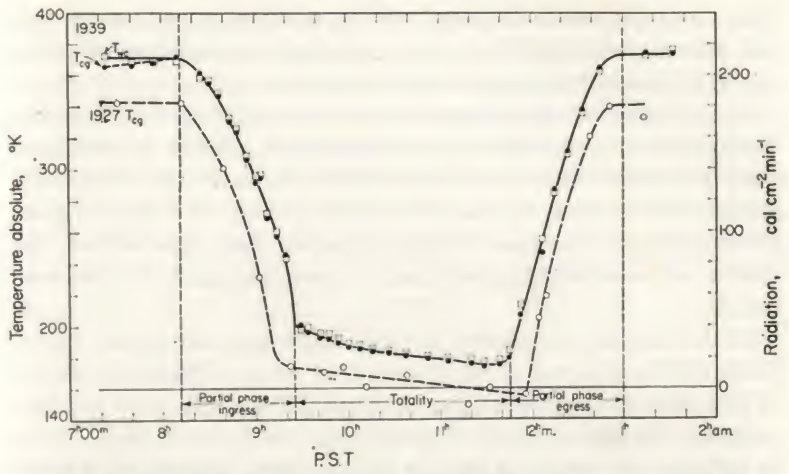

FIG. 7-3-2. Relationships between temperature and time, during the courses of lunar eclipses: Pettit and Nicholson (1930) and Pettit (1940). The broken curve (1927) refers to a region near to the south limb of the Moon. The upper curve (1939) refers to an area of $3.9.10^4$ (sec. arc)², not far removed from the centre of the Moon's disk. (T_{cg} = temperatures recorded when radiation passed through a microscope cover glass filter, 0·16 mm thick; T_{wc} = temperatures recorded when radiation passed through a water cell filter, this being a thickness of 1 cm water contained between quartz windows 1 mm thick.) (*Astrophysical Journal*)

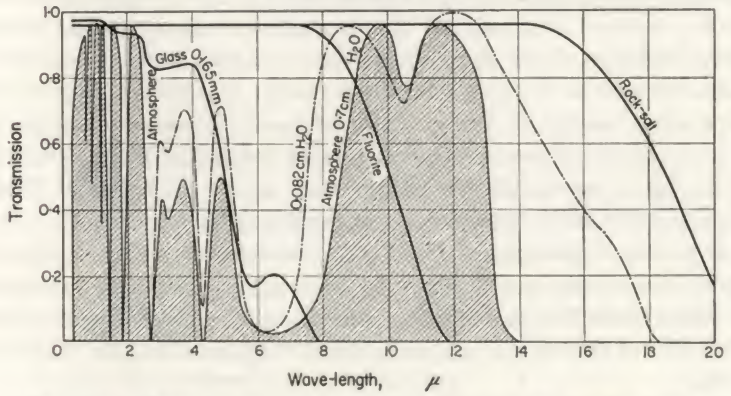

FIG. 7-3-3. Transmission curves: Pettit and Nicholson (1930). Curves are given for the atmosphere above Mt. Wilson (shaded curve); water vapour (0·082 cm precipitable water); glass filter (0·165 mm thick); fluorite filter (4 mm thick); and rock salt filter (2 mm thick). (*Astrophysical Journal*)

glass cover slip which they used, and for a fluorite screen and a rock salt screen. Adel (1946) has more recently determined transmission curves for the infrared spectrum of the Moon.

The reflected sunlight from the Moon is contained mostly in the band 0·3 μ — 5·0 μ, whilst the planetary heat reaches us mainly in the 8–14 μ band. The absorptions between 2 μ and 8 μ are due mainly to atmospheric water vapour. It is seen from Fig. 7-3-3 that the glass cover slip cuts out most of the planetary heat and allows the visible and near infrared radiations to pass through to the thermocouple.

Increasing the sensitivity of the equipment thirty-six times, Pettit (1940) observed a point somewhat removed from the centre of the disk during the eclipse of 27 October 1939, with a 20-in. reflector. He estimated the temperature to fall from 371°K (+98°C) to 200°K (—73°C) during the first partial phase. Then it fell at some 30° per hour, but this rate decreased slowly to 7° per hour at the end of the first hour of totality. At the end of the whole period of totality ($4\frac{3}{4}$ hr) the temperature was estimated to be in the region of 156°K (—117°C) (see Fig. 7-3-2). In this paper, Pettit revised the previous estimate of Pettit and Nicholson (1930) for the temperature of the sub-solar point, from +134°C, to +101°C. The amount of heat coming from the full Moon decreases as one proceeds outwards along a radius of the Moon's apparent disk. The temperatures of rocks exposed normally to the sunlight in polar regions must differ, however, from those of similarly oriented rocks near to the subsolar points by only small amounts, the precise difference depending partly on the amount of heat received by reflection and re-emission from neighbouring rocks and partly on the different heat flux from within the Moon due to the shielding of large areas of the surface in polar regions, by shadows.

It will be noticed from Fig. 7-2-2 that the heat curve reaches a maximum exactly at full Moon (phase angle = 0°). This radiation is being emitted by a very thin surface layer of the Moon. The same is not true of radio-waves, which may penetrate the Moon's surface.

Dicke and Beringer, and Piddington and Minnett (1949) detected radio emission from the Moon on a wavelength of 1·25 cm. (Piddington and Minnett used a 1·7 m diameter paraboloid.) The power received by their radio telescopes was assumed to be proportional to

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the temperature of the source.* Both parties of investigators found that the maximum temperature recorded lagged behind the full Moon by a phase angle of about 50° (i.e. a time lag of about 3·5 days), as shown in Fig. 7-2-2, and this was interpreted as being due to the fact that the Moon's surface layer was partially transparent to the 1·25 cm waves. Hence, the temperatures which were recorded were those of layers at various depths beneath the surface. Piddington and Minnett estimated the mean depth of origin of this energy to be about 40 cm. The temperature which probably prevailed "far below the surface of the Moon" was 234°K (—39°C), and the average surface temperature of the disk of new Moon they estimated to be 145°K (—128°C).

Using a paraboloid of 10 m diameter, centering on a wavelength of 10 cm, Akabane (1955b) determined that the peak temperature at this wavelength was (390 $\pm$ 50)°K and the minimum temperature of the Moon's disk was about (240 $\pm$ 50)°K. There was a periodic temperature variation through about 150°, the maximum temperature occurring a few days after full Moon.

Examining the variations of 3·2 cm radiation with lunar phase-angle, Troitsky and Zelinskaya (1955c) found a fairly uniform temperature of 170°K, with an estimated error of $\pm$15°, but, with Fedoseyev (1959a), they did find a temperature fluctuation (from 190°K, at about 3·7 days after new Moon, to about 260°K, 4 days after full Moon) on a wavelength of 1·63 cm.

Gibson (1958a) used a 3-m-diameter paraboloid which looked at about half of the area of the Moon's disk when centered on the Moon on a wavelength of 8·6 mm. A maximum temperature of 225°K was found about 3 days after full Moon, and a minimum of 145°K about 5 days after new Moon. The observed temperature varied irregularly, rather than sinusoidally, with the phase of the Moon. On a similar wavelength (8 mm), Amenitskii, Noskova, and Salomonovich used a 22 m radio-telescope to find that the recorded temperatures lagged the surface temperatures by a phase angle of about 30° (i.e. a time lag of about 2·3 days). It is not very reassuring to compare this result with that of Gibson.

Grebenkemper (1958b) measured the radiation emitted by the Moon at a wavelength of 2·2 cm, using a 15-m paraboloid. The

* This relationship, for a black body, is well-known in radio astronomy. See, for example, Hanbury Brown and Lovell (1957a).

Moon was examined at different phases, and a maximum temperature of about 210°K determined. The phase-variation of temperature covered a range of only about 25°, the minimum occurring a few days after new Moon.

No positive variation from about 185°K could be detected at a wavelength of 75 cm, according to Seeger, Westerhout and Conway (1957b). They used a 25-m-paraboloid, and the estimated error in the temperature is about 20°. These authors have also quoted unpublished estimates of 208°K and 245°K by J. F. Denisse and E. Le Roux, at 33·3 cm, and by G. Westerhout, at 21·6 cm, respectively. Westerhout's result agrees, within the limits of the errors, with the result of Mezger and Strassl (1959b), who also detected no

TABLE 7-4-1

Author	Wavelength	Maximum temperature (°K)	Minimum temperature (°K)
Pettit and Nicholson (1930)	8–14 μ	342 (near S. limb)	120 (near E. limb)
Pettit (1940)	8–14 μ	371 (near centre of disk)	<156 (centre of disk)
Gibson (1958a)	8·6 mm	225 (central portion of disk)	145 (central portion of disk)
Dicke and Beringer Piddington and Minnett (1949)	1·25 cm	301 (central portions of disk)	197 (central portions of disk) 145 (whole disk)
Zelinskaya, Troitsky and Fedoseyev (1959a)	1·63 cm	260 ± 10 (central portions of disk)	190 ± 10 (central portions of disk)
Grebenkemper (1958b)	2·2 cm	210 (whole disk)	185 (whole disk)
Troitsky and Zelinskaya (1955c)	3·2 cm	170 ± 15 (whole disk)	170 ± 15 (whole disk)
Akabane (1955b)	10 cm	390 ± 50 (whole disk)	240 ± 50 (whole disk)
Mezger and Strassl (1959b)	21 cm	250 ± 30 (whole disk)	250 ± 30 (whole disk)
Westerhout	21·6 cm	245 (whole disk)	245 (whole disk)
Denisse and Le Roux	33·3 cm	208 (whole disk)	208 (whole disk)
Seeger, Westerhout and Conway (1957b)	75 cm	185 ± 20 (whole disk)	185 ± 20 (whole disk)

significant temperature fluctuation at the comparable wavelength of 21 cm.

A clear discussion of many of the above results has been given by Gårstang (1958c).

7-4. Summary of the measured temperatures, and conclusions

In Table 7-4-1, the results have been tabulated in order of increasing wavelength. Where errors are quoted, they are only very rough estimates.

The temperature of a planet is one of the most difficult quantities to measure, and it will be noted that the estimates differ widely. It should be borne in mind that the limit of resolution of the detecting instrument increases as the wavelength of the recorded thermal radiation increases; so that the short-wavelength measurements refer to a specified portion of the Moon's disk, whilst the long-wave measurements refer to the whole disk of the Moon.

Even the microwave measurements integrate the energy emitted from a finite area of lunar surface which has, up to date, been an admixture of continental-type and mare-type material, and one is forced to conclude that the temperature of the lunar rocks at a specified position remains unknown.

Since large fluctuations of the energy emitted in the microwave regions occur as the phase of the Moon varies, and yet no significant temperature variation is observed on wavelengths greater than 3·2 cm, it is reasonable to conclude that the radio-emission at these wavelengths originates at various depths beneath the Moon's surface. For the 1·25 cm radiation, Piddington and Minnett have estimated a *mean* depth of origin of some 40 cm.

The temperature measurements which are most useful are undoubtedly those made with instruments of small limits of resolution. The long wavelength measurements must be thought of as very much averaged values, both across the disk of the Moon *and* in depth.

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CHAPTER 8

The Problem of the Moon's Atmosphere

8-1. Simple visual observations

Many people claim to have seen temporary obscurations of lunar surface detail. Alter (1957a) has reported on the result of a two-and-a-half years' search for such obscurations. His technique was to photograph craters in blue-violet and in infrared light with the 60-in. reflector at Mount Wilson. He found that in Alphonsus, the rille running near to and inside the west wall was generally invisible in blue light, whilst, on the same plate, the rille running inside the west wall of Arzachel, and similarly situated with respect to the sunset terminator, generally remained visible. One possible explanation was that the light from this part of the floor of Alphonsus was being scattered in a layer of gas, but Alter pointed out that the evidence was inconclusive, because there were other equally good explanations of the observed phenomenon. For example, the nature of the ground in the two cases might differ in such a way as to introduce a large difference in the light-scattering properties of the rocks in the neighbourhood of the rilles. Obscurations may also be attributed to the changing conditions in the Earth's atmosphere, differences in the angle of vision, the angle of incidence which the sunlight makes with the Moon's surface, the librations, and the phenomenon of luminescence, and to optical and physiological effects. In view of all the disturbing factors, it is clear that no visual report, even if made in good faith, can provide decisive evidence for the existence of an atmosphere.

It is often stated that the shadows cast by the lunar mountains always appear to be black and sharply defined. This is not by any means true: even in the complete absence of an atmosphere the shadowed regions would often be illuminated by the light reflected from neighbouring brightly-lit mountains. Different shadings in

shadows have often been reported (see 5-1). Also, the tips of long shadows may be extremely ill-defined due mainly to the very large angles of incidence of the adjacent light and the extremely rough nature of the ground, but partly to penumbral effects. The author has never *seen* any penumbral shadows on the Moon, but the possibility remains that they may be detected by photographic or photoelectric means. This test may scarcely be used, therefore, to conclude that the Moon lacks an appreciable atmosphere.

The telescopic view of Mars indicates that surface markings become indistinct as the limb is approached: no such loss of detail is apparent on the Moon. Furthermore, the limb of full Moon is only 10–15% darker than the centre of the disk (see 4-2), and this amount of limb darkening may be accounted for even in the absence of an atmosphere.

When stars pass behind the limb of the Moon, they mostly vanish instantaneously, with no diminution in intensity just before the occultation in question, and with no colour changes. Even assuming that the Moon is devoid of any atmospheric mantle, this cannot be strictly true for stars of large angular diameter, or for stars of any diameter that are occulted twice at the same limb (due to the shape of the limb topography) or at grazing incidence. A discussion of these problems has been given by Evans (1955d).

A delicate test for a lunar atmosphere is to observe the cusps of the Moon for the presence of twilight phenomena. Some observers have reported the appearance of twilight, but these reports may be partly explained by the appearance produced when the Sun's light just catches the tops of innumerable mountain peaks in the polar regions. To see that this is the case, one requires a large instrument in very good conditions. The cusps do sometimes dig into the darkness to a remarkable degree, but the effect described above may be apparently exaggerated if the earthlit limb of the Moon is brighter than the continents situated slightly nearer to the centre of the disk. Russell, Dugan and Stewart (1945) maintain that the absence of twilight phenomena indicates that the upper limit of the ground density of the lunar atmosphere is 10^{-4}, where the unit is the density of the Earth's atmosphere at sea-level.

The important visual and spectrographic observations of Kosyrev have already been discussed in 4-8, and a conclusion has been drawn at the end of this chapter (see 8-4).

8-2. A final solution from the kinetic theory of gases?

According to Wildt (1939), Stoney, in 1897, was the first to point out that the temperatures of the planets bore upon the problem of the escape of their atmospheres. If the molecules at the altitude of the escape layer of a planet's atmosphere are moving at velocities equal to or in excess of the local velocity of escape, they may leave the planet altogether. An important criterion is the temperature at this escape layer. At high temperatures and low pressures molecules may be dissociated into atoms. Ultraviolet radiation has the same effect, and, under the same conditions, the velocities of the atoms would be greater than the velocities of the respective molecules and hence the atmosphere would be dissipated more readily.

Jeans (1925) was able to show, with certain assumptions, that if the root mean square velocity of the molecules of a planet's atmosphere was one third of the velocity of escape, some half of the atmosphere would be lost in a matter of a few weeks. If the molecules had a root mean square velocity of one quarter of the velocity of escape, the atmosphere would not be completely lost even after several thousand years, and dissipation periods of the order of 10^8 years would apply if this velocity were only one-fifth of the escape velocity. At the time of his analysis, it was not known that the temperatures of planetary atmospheres did not necessarily decrease continuously with increase in altitude, and, in fact, Jean's analysis must be modified (Kuiper, 1949a) before it can be correctly applied, for example, to the escape of the Earth's atmosphere. Since the densest possible lunar atmosphere is so extremely rarefied, the exosphere of the Moon must be located close to the Moon's surface, and the relationships found by Jeans may be applied to obtain approximate results. The age of the Moon is very probably of the order of 4 or 5×10^9 years (see Urey, 1956e). According to Jeans, the Moon would retain some atmosphere for at least this length of time if

$$\sqrt{(\overline{v^2})} \gtrsim 0{\cdot}2 v_e\,, \tag{8-2-1}$$

where $\overline{v^2}$ is the mean square velocity of molecules, and v_e is the velocity of escape. Now

$$\overline{v^2} = \frac{3.k.T}{\mu}\,, \tag{8-2-2}$$

where k is Boltzmann's constant, T the absolute temperature in the escape layer, and μ is the molecular weight at the same level, and

$$v_e = \sqrt{\left(\frac{2.G.m}{r}\right)}, \qquad (8\text{-}2\text{-}3)$$

where G is the constant of gravitation, m the mass of the Moon, and r the altitude of the escape layer above the centre of mass of the Moon. Hence, if the Moon was born with an atmosphere, then, even assuming that losses were not replaced by igneous action or by meteoritic impacts (some gas must be generated, continually, by this latter process) one would still expect to find a lunar atmosphere if

$$\mu \gtrsim \frac{75kTr}{2Gm}, \qquad (8\text{-}2\text{-}4)$$

using equations (8-2-2) and (8-2-3) in equation (8-2-1). Taking r as the radius of the Moon, and the temperature as (a) 380°K (day hemisphere) and (b) 120°K (night hemisphere) with the appropriate values of the constants, it emerges that, in case (a) $\mu \gtrsim 6{\cdot}977 \times 10^{-23}$ g, and, in case (b) $\mu \gtrsim 2{\cdot}203 \times 10^{-23}$ g.

The molecular weight is found by multiplying μ, the mass of one molecule, by the Avogadro Number, 6×10^{23}, and is thus, for case (a) 41·86, and for case (b) 13·22.

Kuiper (1949a) said that the Moon would retain an atmosphere if μ was greater than 60. He wrote "SO_2 is interesting because of its large molecular weight. It is produced by volcanic action, as well as by the heating of meteorites and may therefore be present . . . even on the Moon." Because of the large difference between the temperatures of the sunlit and dark hemispheres of the Moon, there would be a tendency for any gases present at sunrise to dissipate preferentially in the direction of the colder hemisphere. It is therefore not clear whether one should consider case (a) or case (b), above. However, even if we take case (a), this means that the Moon may still hold, today, those components of its original atmosphere which have molecular weights in excess of about forty-two.

Unless gases of smaller molecular weight than this accumulated on the Moon much more recently than 10^9 years ago, then all such gases must be absent. With this proviso, the kinetic theory thus states that particles at least more massive than 7×10^{-23} gm (stable

molecules of CO_2, CS, CS_2, H_2S, SO_2, for example) may be present now in the Moon's atmosphere. (But see 8–4.)

8-3. Possible evidence for an atmosphere

The fact that the kinetic theory does not exclude the possibility of the Moon retaining an atmosphere of heavy gases has encouraged many people to devise means of detecting even a very rarefied shell of gas. The evidence presented briefly in this section is subjective and quite inconclusive. In section 8-4, the evidence does not suffer—at least, to the same degree—from these drawbacks.

W. H. Pickering (1895) believed that he had found visual and photographic evidence for volcanic exhalations on the Moon, but he was unable to confirm the presence of a tenuous atmosphere by observations of occulted stars. (The volcanic activity, he said, was dependent upon the altitude of the Sun. A discussion of the origin of such changes as Pickering described will be found in Chapters 4 and 9. It is believed that his explanation of these changes is incorrect.) Again, Pickering (1915) described having witnessed a "snow-storm" over Pico—a most fanciful statement—and he believed (1917) the central mountains of Theophilus to have been carved up by glacier action.

Gordon (1921a) posed the question of how many, if any, lunar meteorite impact flashes would be seen by a terrestrial observer if the Moon had no atmosphere. He estimated that there would be of the order of 20,000 meteorites impinging upon the dark portion of the Moon which could be viewed on an average moonlit night, and asked why at least some of these were not seen. This question was answered by Crommelin (1921b) who pointed out that, for a lunar atmosphere even only 10^{-4} as dense as ours at ground level, the density would be equal to that of the Earth's atmosphere at a height of something over 64 km (40 miles), and at greater heights still, the Moon's atmosphere would be the denser. He said that, since most terrestrial meteors were visible only at heights in excess of 64 km, small particles approaching the Moon would not produce impact flashes, for they would produce meteor trails too faint to be seen from the Earth.

If the assumption is made that the atmospheres concerned are isothermal—a condition which is known to be incorrect for the Earth's atmosphere, but which will be used here for the sake of

establishing an approximate result—one may write, for the Earth's atmosphere,

$$\rho_z = \rho_0 \exp\left[-\frac{g_z M z}{RT}\right], \tag{8-3-1}$$

and for the Moon's atmosphere

$$\rho'_z = \rho'_0 \exp\left[-\frac{g'_z M' z'}{RT}\right], \tag{8-3-2}$$

where ρ_z is the density at height z, ρ_0 is the density at ground level, g_z is the acceleration due to gravity at height z, M is the mean molecular weight (assumed constant), R is the universal gas constant, and T the absolute temperature, and where the primed quantities refer to the Moon. The height in the Moon's atmosphere at which the density is the same as that in the Earth's atmosphere at an altitude z may be found from equations (8-3-1) and (8-3-2), by putting $\rho_z = \rho'_z$, whence,

$$z' = \frac{RT}{g'_z M'}\left(\frac{g_z M z}{RT} - \log_e \frac{\rho_0}{\rho'_0}\right). \tag{8-3-3}$$

In the Earth's atmosphere, meteors become visible between $z = 70$ km and $z = 130$ km. With $z = 130$ km (the upper limit of z), $g_z = 980$ gm cm^{-3}, $M = 28$, $R = 8{\cdot}31 \times 10^7$ ergs deg^{-1}, and $T = 273°$K, z' is positive if $\rho_0/\rho'_0 \leq 6{\cdot}8 \times 10^6$. This means that, with these assumptions, lunar meteor-trails will be seen only if the density of the Moon's atmosphere at ground level is greater than about 10^{-7} of the density of the Earth's atmosphere at sea level, irrespective of the composition of the Moon's atmosphere.*

An experimentally determined upper limit of the ground density of the Moon's atmosphere, in terms of the sea-level density of the Earth's atmosphere, has been reported by Dollfus (see 7-4). If Dollfus' upper limit of 10^{-9} is correct, then impact flashes should occur rather than meteoric phenomena. If, on the other hand, there are lunar meteor trails, then Dollfus' figure is too small. However, a terrestrial meteor-trail of apparent magnitude zero at 100 km

* Vaucouleurs (1947a) said that, for meteor trails to be seen the density of the Moon's atmosphere at ground level must be greater than 10^{-5} of that of the Earth's.

altitude would have an apparent magnitude of only +18 if viewed from the Moon:

$$m_2 - m_1 = 5 \log_{10} \frac{D_2}{D_1}, \tag{8-3-4}$$

where m denotes apparent magnitude and D denotes distance from the observer. Hence, similar meteor-trails close to the Moon would remain unseen even with the largest of telescopes.

La Paz (1938) reconsidered the question of why impact flashes were not seen on the Moon. He showed that, in the absence of a lunar atmosphere, a 10 kg mass with a velocity of 50 km sec^{-1} would have a magnitude of about + 0·6 and hence would be visible from the Earth. The problem seems to be to detect either very faint and very rare meteor trails or very faint and very rare impact flashes. In spite of this, several observers—notably in America—have persisted with their plan to watch the dark side of the Moon for any traces of meteoritic phenomena. One may see what appears to be a lunar meteor and yet the light may originate in the Earth's atmosphere. Misinterpretation can only be ruled out if two observers located at fairly widely separated points on the Earth's surface see a luminous phenomenon simultaneously, and projected on the same part of the Moon's disk. So far, no report has had such confirmation, but Haas (1947b) has recorded ten observations by L. La Paz, E. K. White, and himself, all made between 1941 and 1946, of short, luminous, moving specks projected on the darker portion of the Moon. The lengths of the paths were too short, according to Haas, to have been terrestrial meteors. The paths were bright, as seen across the earthlit surface of the Moon. Haas said that probably no impact flashes were seen.

That even a very tenuous atmosphere would give rise to auroral phenomena on the earthlit portion of the Moon was suggested by Khan (1946a). Such activity could be searched for, he said, via the green ($\lambda = 5577$ Å) and red ($\lambda = 6300$; 6364 Å) emission lines, due to forbidden transitions in neutral oxygen atoms, and the absorption bands in the ultraviolet ($\lambda = 3904$, 3914, 4268, and 4709 Å) due to ionized nitrogen molecules, all characteristic of aurorae. Comparison spectrograms of the ashen light would have to be made with similar spectrograms of the sky adjacent to the Moon, so as to eliminate the possibility of mistaking terrestrial auroral lines with the lines in question.

After Khan's note had appeared, Hertzberg (1946b) described how he had taken sky spectrograms just outside the edge of the illuminated limb of the Moon, and had found a negative result, possibly because the scattered moonlight in the Earth's atmosphere precluded the use of long exposures. Hertzberg suggested that a coronograph be used, but so far this does not seem to have been done. He did not point his telescope at the ashen light because he thought that fluorescence on the illuminated side of the Moon would supply a much more critical test than that suggested by Khan. However, spectrograms were taken in the ultraviolet by Kosyrev (1956b) with the 50-in. reflector of the Crimean Observatory and exposures of one hour, and Kosyrev did not report on the presence of absorption bands due to ionized nitrogen molecules (see 4-7).

8-4. Evidence from more refined techniques

The classical methods of investigation are (a) the refraction of light from a distant source when the Moon passes in front of it and (b), the variation in the proportion of polarized light across the disk of the Moon. Both methods give negative results.

The first to use a polarimetric technique for examining the possibility of the Moon having an atmosphere, Fessenkov (1943) examined the central region of the Moon's disk with a polaroid filter at times of quadrature, looking in fact just to the darker side of the terminator. If the Moon possessed an atmosphere, the light diffused in it at this place would be polarized, but Fessenkov detected no change in the brightness of the observed areas when the polarizing filter was rotated. Assuming that the coefficients of scattering in the Moon's and in the Earth's atmosphere were the same, he said that an atmosphere of vertical mass 10^{-6} of that of the Earth's atmosphere would have been detectable. A résumé of this paper was given by Struve (1944). Fessenkov's quoted precision suffered destructive criticism by Lyot and Dollfus (1949b) who pointed out that the ashen light was itself strongly polarized and was some 100 times brighter than such an atmosphere.

Following Fessenkov's idea, Lipski (1949c) again observed the centre of the Moon's disk at first and last quarters, but this time with a photo-polarimeter utilizing green light centering on 5300 Å. He deduced that the density of the Moon's atmosphere at the surface of the Moon was probably not more than 10^{-4} times that of the Earth's at sea level.

Lyot and Dollfus (1949b) aimed at increasing the precision of the visual method of observing lunar twilight, a method first proposed by Russell, Dugan and Stewart (1945). They used the 20-cm coronograph at the Pic-du-Midi Observatory, and reported the sky brightness near to the cusps at time of quadratures to be less than 10^{-6} stilb.* On a very clear night, an exposure of 30 min could be given with a yellow filter (Wratten K3), the coronograph looking at that part of the sky which was adjacent to a cusp. Guiding was accomplished by means of an auxiliary optical system.

The intensity distribution across the plates, measured microphotometrically, was found to be quite different from that which may be observed to hold at the same phase for a planet with an atmosphere, and could be explained by the diffusion of moonlight, irradiation of the ashen light, and by the Eberhard effect. Lyot and Dollfus reckoned that an atmosphere brighter than $5{\cdot}7 \times 10^{-8}$ stilb would have been detectable, and had the ground density of the atmosphere been in excess of 10^{-8} of that of the Earth's, it would have been easily detectable.

Proceeding to a still more sensitive method, Dollfus (1952) adapted a projection lens and Savart-Lyot polariscope to Lyot's coronograph and arranged a second lens to project the image of any fringes on a photographic plate. The contrast between such fringes increases as the proportion of polarized light of the source increases. In front of the first lens, two plates of thin glass were placed, capable of rotation about axes parallel to and perpendicular to the fringes, to introduce auxiliary polarizations. These plates could double the sensitivity of the instrument, and compensate for the polarization of the luminous background.

On the 25 April 1950, the sky at the Pic-du-Midi was exceptionally clear and an exposure of about an hour was given on Eastman 103aE plates with an orange filter (Wratten 12). The sky background was only $1{\cdot}6 \times 10^{-7}$ stilb—one-sixtieth of the brightness of the ashen light. Dollfus estimated that the brightness of the lunar atmosphere was $\leqslant 5 \times 10^{-9}$ stilb. For an atmosphere of carbon dioxide, this would correspond, he said, to a ground density $<0{\cdot}5 \times 10^{-9}$ of the Earth's. Dollfus indicated that still greater sensitivity could be achieved by operating with a half-wave plate in violet light: with such

* The stilb is a measure of the luminous intensity per unit projected area, 1 stilb = 1 lumen cm^{-2} $sterad^{-1}$.

wavelengths the atmosphere and the background would be brighter, in accordance with the λ^{-4} law, but the moonlight itself would be fainter. A résumé of previous work has been given by Dollfus (1956a) and his previous conclusions have been left substantially unmodified.

Öpik (1955a) drew attention to the large difference in the upper limits of the relative ground density of the Moon's atmosphere as deduced by Lipski (10^{-4}) and Dollfus (10^{-9}). Öpik said that if the real figure were as large as 10^{-4}, lunar twilight would be prominent. Öpik's observations indicated that, about three days before first quarter, any twilight could not have been more than a quarter of the brightness of the neighbouring ashen light and, at a phase angle of 83° (just after first quarter), any twilight could not have been more than half as bright as the near-by ashen light. He proceeded to show that the maximum density compatible with these observations was some 100 times smaller than Lipski's estimate.

Kuiper (1949a) made spectrograms of the Moon in the range 3000–3180 Å and found that neither those of the centre of full Moon nor even those of the extreme edge of the disk showed any trace of SO_2. On the assumption that an equivalent thickness of 0·02 cm of SO_2 at standard temperature and pressure (S.T.P.) would have been detectable in the limb spectrum, he concluded that the equivalent thickness of SO_2 in the Moon's atmosphere was $<0{\cdot}0003$ cm, reduced to S.T.P.

Accepting Dollfus' upper limit of 10^{-9}, Kuiper (1955c), writing in the *Transactions of the International Astronomical Union*, said that the absolute density of the Moon's atmosphere at the surface of the Moon was less than the density of the Earth's atmosphere at an altitude of 180 km, and that, since this was far above the meteor zone, the reports of lunar meteors having been seen (see 8-3) must be false. Kuiper said that on very rare occasions explosions on the Moon might perhaps be visible.

On the assumption that the radioemission from the source 2C.537 of the Cambridge Survey was concentrated in a particular part of the source, Elsmore and Whitfield (1955b) found that, using the observation that the delay produced by refraction in the lunar ionosphere and diffraction at the Moon's limb did not exceed four minutes of arc, the electron density in the lunar atmosphere could not exceed 10^5 cm^{-3} if the scale height lay in the range 50–1500 km

(i.e. the height of the Moon's ionosphere as compared with the height of the Earth's). Whence, they deduced that the atmospheric density at the surface of the Moon was 10^{-12} of that of the terrestrial atmosphere at sea level. This result has been the subject of criticism (1956c) based upon the errors of observation, yet an upper limit of 10^{-13} has been determined by Costain, Elsmore, and Whitfield (1956d). Edwards and Borst (1958) have suggested that the heavy gases xenon and krypton may still be present on the Moon: these gases may have been present primaevally, or they may be produced by the spontaneous fission of U-238 or by the radioactive decay of I-129 into Xe-129. However, accepting Costain, Elsmore, and Whitfield's value for the electron density, namely 10^3 to 10^4 electrons per cubic centimetre at the Moon's surface, Öpik (1957b) has noted that krypton and xenon, having low ionization potentials, must be ionized by the solar ultraviolet light and hence must escape from the

TABLE 8-5-1

Author	Method	Maximum density of Moon's atmosphere. (Density of Earth's atm. at sea-level = 1)
Russell, Dugan, and Stewart (1945)	absence of twilight	$<10^{-4}$
Lipski (1949c)	photography of twilight in green light, with a polarimeter	$<10^{-4}$
Lyot and Dollfus (1949b)	photography of twilight in yellow light, with a 20 cm coronograph	$<10^{-8}$
Dollfus (1952) (1956a)	photography of twilight in orange light, with a 20 cm coronograph and Savart–Lyot polariscope	$<10^{-9}$
Elsmore and Whitfield (1955b)	refraction of radio waves in lunar ionosphere	$<10^{-12}$
Costain, Elsmore, and Whitfield (1956d)	refraction of radio waves in lunar ionosphere	$<10^{-13}$

Moon. Again, Herring and Licht (1959) have pointed out that solar protons of velocities $\sim 10^8$ cm sec^{-1} will occasionally collide with any atoms of a lunar atmosphere and impart escape energies to them.

In spite of the undoubtedly very low upper limit of the density of the lunar atmosphere, it is clear that, if one accepts the observations of Kosyrev (see 4-8), the gas density at a given point on the Moon's surface may instantaneously assume a relatively high value.

8-5. Summary of the estimates of the density of the Moon's atmosphere

The upper limits of the Moon's atmospheric density, as estimated by different methods, are listed in Table 8-5-1. The results are not contradictory, since only upper limits have been given, but no attempt to weight the values will be made here.

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CHAPTER 9

The Probable Nature of the Moon's Surface; Changes which occur on the Moon

9-1. Deductions from the size and mass, from the figure, and from the surface structures of the Moon

The Moon is massive enough to produce appreciable compression at its centre, but its mass is too little to produce a state of degeneracy at the centre. Its mean density is about 3·34 g cm^{-3} and the surface materials probably have an average density which does not differ very much from this mean value.

That the Moon is probably not in a state of hydrostatic equilibrium indicates that the materials which compose it must have appreciable strength.

Seismic waves seem to have pervaded the interior, judging by the grid pattern (a physical pattern composed of criss-crossing linear features, discussed in Chapter 11), and this energy may possibly have been derived from the local excesses of gravitational potential (present by virtue of the non-isostatic shape of the Moon), gravitational shrinkage, body tides, or large-scale impacts.* Adjustments of the surface have taken place as a consequence of these disturbances. Gilvarry (1957a) has suggested that lunar seismic action erodes the rocks and tends to powder them. Rock dust would then be transported to the lower levels by the same seismic activity. This process must have operated.

Darling (1942) appreciated that the large numbers of small meteorites hitting the Moon daily, since its accumulation was complete, must have fragmented the surface layer of rocks. Sytinskaja

* Some ideas on the effects of impacts of comets have been presented, recently, by Kopal (1959a; 1959c) and criticized by van Dorn (1959b).

(1959h) maintains that meteoritic action* must have transformed the lunar surface into a highly porous, slag-like material.

Igneous rocks might be found within craters of igneous origin (see Chapter 12).

9-2. Deductions from the intensity variations and from the colour of moonlight

All the observations of the manner in which the intensity of the light from the Moon varies with phase angle support the supposition that, in addition to the surface being very mountainous, the fine structure must, in similar fashion, be far from smooth. Because of their small albedos, a lava character has on several occasions been suggested for the maria. No models truly representative of the surface have yet been proposed, but Schoenberg's suggestion of loose stones would be in agreement with the statement made above (9-1) concerning the action of meteorites.

Again, in support of the presence of large numbers of unresolvable surface indentations is the fact that the variation in the colours of a particular spot may be explained by the shadows trapped by such indentations at certain phases. By a study of both the light and the heat coming from the Moon, Sharonoff (1954c) was led to propose that the surface was covered with a "spongy, vesicular clinker" formed by subsurface explosive activity and by the action of meteorites.

The continents probably differ from maria in chemical composition. The fact that the seas reflect more green light than the continents does not by itself imply a difference in chemical composition, but Dubois has detected differences in the luminescent properties of the lunarite and marebase (4-7). Studies of the type of luminescence which is exhibited by certain spots will, it seems, help to identify individual minerals which are exposed on the Moon's surface.

At the present time, it is still difficult to generalize about the chemical nature of the lunar rocks, since some of the evidence which has been presented in support of the presence of certain substances is conflicting. However, more than once, students of the colour of moonlight have suggested lavas for the seas and have associated powders of transparent substances with the surface as a whole.

* Rocket counts have given 1 micrometeorite. cm^{-2} min^{-1}. Whipple (1959j) estimates that the Moon has received ~ 2 kg cm^{-2} of meteoritic material in its lifetime.

9-3. Deductions from the polarization of moonlight

It has long been difficult to understand why the lunar surface polarizes the incident light to such a small extent. Laboratory tests showed that rocks had to be in the form of *coarse powders* if they were to polarize as much unpolarized sunlight as possible, but even fine powders polarized more than the Moon (see 6-1). Iron meteorites polarized too much light. Kosyrev pointed out that iron could not be present in luminescent spots (see 4-7). In agreement with the deductions given in 9-2, powders of transparent substances have been suggested by F. E. Wright, since they yielded small polarization angles like those observed for the Moon.

9-4. Deductions from the observed temperature changes*

Coblentz (1907) noticed that, although Langley's curves showed a fall in heat almost coincident with the fall in illumination at the commencement of an eclipse, some heat appeared to be emitted even in the umbra. Measurements of the amount of heat emitted by the Moon at given times after the beginning of an eclipse of the Moon would obviously yield information about the thermal properties of the surface layers.

An attempt to evaluate the product $k\rho c$ for the Moon, where k is the thermal conductivity, ρ the density, and c the specific heat of the near-surface layers, was made by Epstein (1929) by treating the Moon as a semi-infinite solid and adjusting the variables to fit as closely as possible the eclipse curve of Pettit and Nicholson. However, there was an error in his reasoning, as pointed out by Jaeger and Harper (1950), and his result is not valid. But at least Epstein inspired others to follow his basic idea (see below).

It is known that silica, and the silicates in general, exhibit high reflecting powers in the region 8–14 μ. By means of a fluorite screen, Pettit and Nicholson (1930) found that the radiation coming from the region isolated between the glass and fluorite screens was roughly of the same intensity as that coming from the whole 8–14 μ region (see Fig. 7-3-3). Hence, if silica had been present, it must have been acting like a black body, and hence, the authors concluded, it must have been finely divided.

* *Note.* In this section, evidence associated with the thermal conduction properties of the lunar rocks is first reviewed. A summary has been provided at the end of the section.

From simple considerations of the rate of fall of temperature during the total phase of a 1939 eclipse, Pettit (1940a) found that the depth of rock which was immediately involved in the exchange of radiation during the eclipse was of the order of 3 cm.

The non-linear thermal conduction equations were solved numerically by Wesselink (1948) and he obtained

$$(kc)^{\frac{1}{2}} = 0{\cdot}0011 \text{ c.g.s. units},$$

from Pettit's (1940a) eclipse data. With $c = 0{\cdot}2$ cal g^{-1} (C°)$^{-1}$, (the value for common rocks), this yields

$$k = 6 \times 10^{-6} \text{ cal cm}^{-1} \text{ sec}^{-1} (\text{C°})^{-1}.$$

This figure is very small and, with $\rho = 2{\cdot}0$ g cm^{-3}, corresponds to a value of $(k\rho c)^{-\frac{1}{2}} \approx 640$. Comparison values for other media are given in Table 9-4-1 (orders of magnitude only).

TABLE 9-4-1

Medium	$(k\rho c)^{-\frac{1}{2}}$
Granite	20
Basalt	20
Pumice* (1 atm. pressure)	100
Dust (*in vacuo*)	500 (Kannuluik and Martin) 1000 (Smoluchowski)

* If the bubbles in the pumice did not contain any gas, then the order of magnitude of the quantity $(k\rho c)^{-\frac{1}{2}}$ would probably not change.

The values quoted for dust are from two sources. Firstly, the thermal conductivities of evacuated powders were found by Kannuluik and Martin (1933) to be consistently of the order of $1{\cdot}0 \times 10^{-5}$ cal cm^{-1} sec^{-1} (C°)$^{-1}$. Secondly, Smoluchowski (1910) made some measurements of the thermal conductivities of several powders under pressures down to 0·05 mm of mercury. He found $k = (3{\cdot}3 \pm 1{\cdot}8) \times 10^{-6}$ cal cm^{-1} sec^{-1} (C°)$^{-1}$, for all the powders which he investigated, and he gave the formula $k_{\text{vacuo}} \simeq 0{\cdot}01\ k_{\text{one atm.}}$

Schumann and Voss (1934) showed that, for a system of particles in vacuo in which the particles touched in points, the equivalent conductivity of the system would be zero. In practice, there was a residual conductivity as the pressure was reduced to zero, due to the fact that the particles always made contact over a finite area.

Wesselink (1948) estimated the temperature in the inner part of the Moon to be 212°K (—61°C). He noted that pumice, which had been proposed as a surface material by Epstein, was not adequate to account for the lunar data, but that powders *in vacuo* had sufficiently small values of the constant k. Wesselink said that the grains on the surface of the Moon must be less than 0·3 mm in diameter, and he found reasons to suppose that k would vary with temperature, particularly if the grain size lay between 0·1 and 0·3 mm, but to an unimportant degree if the grains measured less than 0·1 mm across.

From Pettit's and Nicholson's eclipse data in the infrared and their own radio observations of the Moon during an eclipse, Piddington and Minnett (1949b) found that both sets of data could be fitted by applying the condition

$$d = 610k(k'\rho'c')^{-\frac{1}{2}}, \qquad (9\text{-}4\text{-}1)$$

where d and k were the thickness and thermal conductivity of a skin of material lying upon a substratum having constants k', ρ', and c'. The reason for choosing a model of this sort is that, unlike the infrared radiation, which comes principally from a thin surface layer, the radio emission originates in deeper layers in the Moon. *One* possible interpretation of the results was that the moon-crust material was of solid rock, covered with a layer of (meteoritic) dust. If the substratum was similar in conductivity to terrestrial rocks or lava, then the dust film would, they said, be very thin—of the order of 1 mm.

Jaeger and Harper (1950) examined both Pettit's and Nicholson's, and Piddington's and Minnett's data. They found that the condition $(k\rho c)^{-\frac{1}{2}} = 1030$ c.g.s. yielded a curve which approached closely the eclipse curve of 1939, although it did not fit it exactly. The explanation of this deviation seemed to Jaeger and Harper to be that the solid was not homogeneous. Jaeger and Harper had thus arrived at the same general conclusion as Piddington and Minnett. The possibility that k depends on the temperature should, however, also be considered. Muncey (1958i) has drawn attention to the fact that, if k and c are proportional to the absolute temperature, the $(k\rho c)^{-\frac{1}{2}}$ could be as small as 200 or 300 at 300°K, rather than as large as 1000 c.g.s. The data on the variation of these contants with temperature appears to be inadequate.

Taking $k = 2{\cdot}8.10^{-6}$ in equation (9-4-1), compatible with $(k\rho c)^{-\frac{1}{2}} = 1030$, $c = 0{\cdot}2$ and $\rho = 1{\cdot}7$ (c.g.s. values of these constants for dust), Jaeger and Harper varied $k'\rho'c'$ and d to find that the best fit to the eclipse curve was given by $d \approx 2$ mm, $(k'\rho'c')^{-\frac{1}{2}} \approx 100$. The substratum therefore corresponded to "terrestrial values for substances such as pumice or gravel . . .". By constructing a curve for bare rock with $(k\rho c)^{-\frac{1}{2}} = 20$, the authors found that not more than about 5% of the region which had been observed could have been of this material.

Lettau (1951) assumed that the quantity $k/\rho c$ was a linear function of the depth. Pettit's eclipse curve could be approximated by means of this model if the Moon had a cover of dust of average thickness 0·5 m, overlying solid rocks.

An alternative model—and, incidentally, a more practicable one—has been proposed by Fremlin (1959f), in a reply to Jaeger (1959e) who pointed out that the heat flux assumed by Fremlin (1959d) on a previous occasion was probably much too high, and that the value of the thermal conductivity of dust which Fremlin used was probably much too low. In his reply, Fremlin suggested that, instead of assuming the presence of a uniform layer of dust covering a substratum of different conductivity, a more reasonable hypothesis was to assume that there were patches of bare rock and of dust exposed on the Moon's surface. Taking $(k\rho c)^{-\frac{1}{2}} = 20$ for bare rock, and 2700 for dust, Fremlin got an almost exact fit with Pettit's observational curve in the case when bare rock covered 4·8% of the surface. By allowing for differing albedos and kinds of rock, Fremlin said that there would be no difficulty in employing a value of k, for dust patches, even lower than that assumed in his previous paper.

Buettner (1952a) noted that the eclipse measurements of 1927 and of 1939 were made on different kinds of topography: in the first case, a mountainous region near to the south pole was observed, but in the second case the area observed was near to the centre of the disk, and contained some marebase materials. The two curves were, however, very similar, and Buettner concluded that "steep mountain slopes" showed the same value of $k\rho c$ as "level surfaces". He thought that dust was unlikely to contribute much bulk to the surface layers, because meteoritic impacts would have caused the material to "glide down the slopes". This is not so feasible as it sounds, because mountain

slopes are, on average, not steep, and have complex terraces. It would be desirable to have an eclipse curve of a region which contained no lunarite at all. (He suggested that the principal erosional mechanism was cosmic-ray primaries which caused disintegration of the crystalline structure of the rocks.) On the other hand, Gilvarry (1958k) used the same data to argue that the lunar mountains must be covered with dust. Clearly, the observational methods are not sufficiently selective: better resolution is required.

Closing the gap in the data between 14 μ and 1·25 cm, Sinton (1956a) observed a total eclipse of the Moon in a waveband centered on 1·5 mm. His apparatus was a 61-cm diameter searchlight mirror and a Golay infrared cell. The cell was calibrated by pointing the apparatus at the Sun and assuming the Sun to have an effective temperature of 7000°K in the wavelength 1·5 mm. The field used was of about the same angular size as the disk of full Moon. Sinton observed a decrease of the emission which lagged behind the visual eclipse by about an hour, indicating a sub-surface origin for the radiation. He found that the average mass-absorption coefficient of the whole lunar surface was 2·9 $cm^2\ g^{-1}$, and that laboratory experiments with the same apparatus gave mass-absorption coefficients of 7·0 $cm^2\ g^{-1}$ and 1·54 $cm^2\ g^{-1}$ for a stony meteorite and for basalt, respectively. Sinton pointed out that, if this meteorite was typical, the whole surface was probably not completely covered with dust.

Working on a wavelength of 8·6 mm, Gibson (1958j) detected no definite change in the radiation during the first few hours of each of two eclipses.

Summary of section 9-4.

The surface layers of the Moon are composed of materials which are, on average, poor thermal conductors. If silicates are the main constituent of the lunar surface, they are probably finely divided. Powdered rocks *in vacuo* have thermal properties similar to those of the lunar surface materials. Rock dust would be expected, for instance, as a result of the impacts of meteorites. Pumice does not fit the requirements for the surface material. However, the observations always apply to large areas of the Moon's surface, and materials other than dust may well be found exposed on parts of the surface and, in fact, it is clear from their structure that the mountains cannot

be composed of dust. The mountains are not steep and there may be frequent pockets of dust trapped in declivities which have smaller slopes than the average and in between terraces in the mountains, giving a *mean* dust cover over the mountains of only a millimetre or so. For the region observed by Pettit in 1939, which contained some lunarite and some marebase, only about 5% of the area could consist of exposed granitic or basaltic rock faces.

Micro-waves have been used to probe deeper into the Moon and indicate that, averaging over the whole disk, there may be a dust layer underlain by a better thermal conductor.

No measurements made so far refer purely to marebase materials. Thus, no estimates of the composition of maria have direct experimental backing. This is unfortunate, because the interesting question "How deep is the dust in the lunar seas?" remains unanswered. Not only are further infrared observations required; radio-telescopes with the smallest possible limits of resolution should be directed at particular parts of the Moon's surface.

9-5. The effect of the absence of an atmosphere

What effect would unimpeded solar radiation, of all wavelengths, have on the surface of the Moon, and what other forces would play on the surface in the absence of an atmosphere?

Large meteorites would reach the Moon whether or not it had a rarefied atmosphere, but micrometeorites would be ionized in flight if there were even only a very tenuous gaseous envelope. The effect of micrometeorites, which occur so much more frequently than larger ones, would therefore be important if the Moon had no atmosphere. This effect has already been discussed (9-1).

A more difficult question concerns the action of infrared and ultraviolet radiation, and X-rays, on the lunar rocks. T. Gold (1955b) has suggested that ultraviolet radiation and X-rays act in such a way as to break down rock particles into grains of minute sizes, and that these grains of dust behave rather like a dense gas, bound very close to the Moon's surface and flowing to the lower levels. There appears to be some experimental evidence (1960b) in support of this idea, but Whipple (1959j) believes that corpuscular radiation would "cement" the dust and prevent it from flowing. Gilvarry (1957a) suggested that the movement of the dust could be explained by postulating seismic action.

The thickness of the layer of dust in the models of Pettit and Nicholson (1930) and of Jaeger and Harper (1950) was of the order of 1 mm, but this was an average value for special parts of the Moon. Hence the actual thickness of dust at a given part of the surface is not known. Buettner (1952a) has pointed out that "only radio data from small regions of the lunar surface can give new information". There is not even any experimental evidence for the much quoted mechanism of fragmentation of the lunar rocks by alternate heating and cooling. Clearly, experiments must be performed *in vacuo*, and in the absence of moisture, before such mechanisms as these can be used convincingly in our arguments.

Another possibility is that cosmic rays have caused erosion of the lunar rocks. Buettner suggested that cosmic ray primaries caused disintegration of the crystalline structure of the rocks, and Whipple and Fireman (1959g) estimated an upper limit for the rate of erosion of an iron meteorite of $1{\cdot}5.10^{-7}$ cm yr^{-1}. At this rate, a lunar mountain would have suffered a few metres of erosion due to cosmic rays, since it was formed.

High energy particles from the Sun are bombarding the Moon. It seems not impossible that, in the absence of a conventional type of atmosphere, there is an electrical "space charge" close to the Moon's surface during the lunar day. In such a case, particles would be in a state of dynamical equilibrium. If there is no such space charge, one may expect the electron density close to the surface of the Moon to be of the order of 10^3 or 10^4 electrons cm^{-3} (Brandt, 1960c). Examining the results of radar studies (1957c), Gold (1959j) suggested that the Moon's surface was very smooth down to sizes of the order of 10 cm; yet Hughes (1960d) measured the angular scattering properties of the Moon at a wavelength of 10 cm and found his results to be consistent with surface irregularities having vertical dimensions much greater than this wavelength. Further work is required on this subject: the apparent smoothness of the Moon as a reflector at certain radar frequencies may even be connected with the presence of lunar "space charge" or ionosphere. At these frequencies, the scattering properties of the Moon may differ in the day and night hemispheres. Certainly, the results at optical frequencies do not suggest that the micro-structure of the Moon's surface is smooth.

9-6. Changes in the Moon's surface: Apparent and real

(a) *Apparent changes in physical relief.* On several occasions in lunar observational history, permanent changes have been reported in the surface structure, but no visible changes in structure have ever been established. The most frequently discussed* change concerns the small formation Linné which appears on many photographs as a whitish patch in Mare Serenitatis. According to the 1867 *Report of the British Association*, Schmidt, Lohrmann, and Mädler frequently described Linné as having been a deep crater prior to 1843. In 1866 it was found that the crater had disappeared. However, the author, observing with the 18-in. reflector of Manchester University, saw Linné again as a crater in 1955. The following extract is from the author's observing notes made at the time of the observation: "Linné looked (8 September 1955, $01^h\ 30^m$ U.T.) almost like a normal craterlet†, with a bright part to the east (which might be interpreted as an eastern ringwall) and a shadowed (slightly smaller, perhaps) part to the west of this." Again, Rambaut (1903b) unearthed a drawing of Mare Serenitatis made by the professional artist John Russell on 12 April 1788. Russell indicated Linné by means of a white patch, as it is usually seen today. This drawing was made at nearly the same phase as Schroeter's drawing‡ of 5 November 1788.

Clearly, the evidence is conflicting, and the writer would support Saunder's (1904) conclusion, based upon a re-examination of the drawings, that the answer is uncertain, but that probably no change is indicated.

(b) *Real changes in physical relief.* Impacts of meteorites must be slowly wearing down elevations. The effects produced by solar radiation are less certain (see 9-5). No changes have been established inside Alphonsus, after Kosyrev's reported observation of gaseous activity from within the Moon (4-8). Body tides must, of course, be present.

(c) *Quasi-periodic changes.* Of historical interest are the series of papers written by Pickering (1919; 1921; 1922; 1924a; 1924b;

* See, for example, references 1895a; 1895b; 1903a; 1903b; 1904; 1915.

† This is not be confused with the much smaller, central craterpit, the diameter of which in only about 900 m and which has a wall not higher than 30 m above the surrounding country, according to Dollfus (1955c). The craterpit can be seen only under grazing illumination and with very good seeing conditions "with a good telescope of 15 cm aperture". The craterpit has been photographed.

‡ See *Selenotopographische Fragmente*, **1**, plate (ix).

1924c) on the changes in intensity within the crater Eratosthenes. The changes (which Pickering attributed to the periodic movements of migrating creatures) may be due to the structure of the terrain, the different albedos of the substances composing it, and to the phenomenon of contrast.

The floor of Plato has for long been a subject of interest; Carle (1955a) has discussed the interesting features of this crater. At a given phase, markings such as small craters may be seen on the floor of Plato. Yet, under apparently equally good seeing conditions and at almost the same phase, observers report the complete absence of such markings. Should the visibility of these small structures be so critically phase-dependent? The observer gains the impression that these are temporary mists inside Plato, but there can be no gas in sufficient quantity to produce such mists. It is possible that luminescent effects are present (see 4-7), rendering some patches more conspicuous during periods of more intense solar activity. The phenomenon of luminescence might contribute to the Linné mystery (4-4), too. It is, of course, understandable that the display of detail on the floor of Plato differs at different phase angles: that the eye can err by a considerable amount when judging the intensity of the floor of Plato has been demonstrated by the instrumental results of Wirtz (see 4-3).

Unexpected phase-variations of the intensity of the light reflected by certain spots have been discussed already (4-4). A light patch, seeming to indicate a central mountain, has been seen in Herodotus by Wilkins and, at two different times, by Bartlett (1954a), yet Bartlett was unable to find the light patch on later occasions. Rosebrugh (1954b) suggested that Bartlett's observations would be explained by assuming that the sunlight had been reflected from the inner, eastern ringwall of Herodotus by a field of specially-oriented rock-crystals, such as feldspar. However, one should always be wary of unusually bright light-spots on the Moon, as they may be optical "ghosts" in a telescope. It is noteworthy that no new crater has been detected where Stuart (1956b) observed what he thought to be a meteorite exploding.

9-7. Are tektites samples from the Moon?

Tektites are dark, glassy objects (mainly silica) which are found only on some parts of the Earth's surface. They do not seem to be related

to the terrestrial rocks on (or in) which they are found; and their density is only 2·4 g cm^{-3}. Some are hollow: the gas pressure inside these hollows has been found to be less than 10^{-3} atm. Tektites contain remarkably little water of combination—less than in any terrestrial rocks known. The shapes of tektites vary, and have been modified by passage through the atmosphere: characteristically, they assume rather symmetrical shapes, such as button-shapes or ovoids, but originally they must have been spherical, dumbell- or pear-shaped, and they must then have been molten. Next, they cooled and solidified, and, finally, they were heated aerodynamically in such a way that only a thin skin melted across the leading face of each object. In all cases, this leading face is defined by the position of stability of a tektite at velocities similar to those which prevailed when the tektite entered the Earth's atmosphere (Chapman, 1960; see below).

A small map, showing the principal areas where tektites have been found, has been published by Nininger (1947). In a given locality they are alike, but different groups are composed of specimens which may differ in colour, form, and percentage-composition—although, qualitatively, their compositions do not differ. Of concern here is the outcome of the long controversy which has dealt with their postulated lunar origin.

Reviews of earlier theories have been executed by Barnes (1940b) and by Eiby (1959i). In addition to proposing that tektites were fragments which had arrived from the Moon, as meteorites, Dietz (1946) suggested that the lunar rays were made up of tektites—a proposal which has been revived by Gold (1958c).

At first supporting an extra-terrestrial origin for tektites, Urey (1955d) reconsidered the question and, from considerations of the chemical composition and the distribution of tektites, came to the reverse conclusion, in support of Barnes. Later, Urey (1957b) put forward the tentative idea that comet impacts with the Earth might have produced tektites.

Recently, O'Keefe (1958a) and Varsavsky (1958b) maintained that the distribution of tektite-areas was plausible if the particles had arrived from the Moon, but opposing views have been presented by Barnes (1958d) and Urey (1958e), and Kopal (1958f) has pointed out that Varsavsky's analysis is open to misinterpretation and that his results cannot claim any particular significance. Kopal has further

suggested that comparison luminescence-spectra of tektites and the lunar rays be made. The luminescence-spectra of different groups of tektites may, however, differ, and so this test would not necessarily provide a solution to the problem.

Kohman (1958g) suggested that tektites originated outside the solar-system, but Urey (1958h) attacked this view because, he said, Kohman disregarded the fact that the chemical composition of tektites was very similar to that of certain sedimentary rocks. Also, tektites showed evidence of having been melted and this point was also not considered by Kohman.

Evidence pertinent to the origin of tektites has now been collected by Chapman (1960a). From both theoretical and experimental (wind tunnel) studies of the ablation patterns on some australites (the most recent and best preserved tektites, thought to be about 5×10^5 years old) Chapman has shown that the velocities with which these objects entered the upper atmosphere lay between 12 and 13 km sec^{-1}. This important criterion not only rules out a terrestrial origin for the tektites, but also indicates that they originated in an orbit around the Sun similar to the Earth's orbit.

The low gas pressure inside the hollows, the radioactive content, and the extremely low water content of tektites are all consistent with a lunar origin, although no proof has been given that these objects came from the Moon.

Chapman maintains that meteoritic impacts could not transfer sufficient energy to solid rocks to melt them, but that vesicular rocks could be melted in this way. Thus, he reasons that, if tektites represent parts of the Moon's surface, they were possibly ejected from vesicular areas such as maria. However, if the materials of the Moon have not been differentiated by radioactive heating and gravity, one would have to explain why the density of tektites is so much smaller than the mean density of the Moon (2·4, as opposed to 3·3 g cm^{-3}). There appear to be three possibilities: (a) towards the end of the formation of the Moon itself, it accumulated low-density objects; (b) the materials forming the Moon have, in fact, suffered differentiation; (c) tektites do not originate on the Moon.

The observed distribution of tektites on the Earth still lacks adequate explanation. (The observed distribution is, of course, subject to geographical and geological selection.) Much more work remains to be done on this subject.

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Part II

CHAPTER 10

Ray Systems

10-1. General description

These appear as permanent streaks which cross over the lunar surface. Known examples are usually very much brighter than their surroundings, and are probably always associated with a relatively young crater. (The relative ages of two craters may be judged, for example, by considering which overlaps the other.) Craters which show evidence of much erosion do not exhibit rays. The rays diverge from some craters, where they are densest, to distances which are often of the order of ten diameters of the crater, becoming sparser as the distance from the crater is increased. For this reason, the positions of the ends of the rays cannot be determined accurately.

In the great majority of cases the rays are roughly straight and they nearly follow great circles which intersect at the centre of a crater. However, it is more correct to say that the rays do not, in general, intersect in a point, but collect within the circle defined by the walls of the crater in question. Thus, some rays appear to originate in the walls of craters, rather than in their centres. Again, some rays appear to commence outside the walls of a crater, and characteristic, dark haloes may be left encircling these craters. Sometimes the rays appear as curves other than great circles. In these cases, they may often be described as elliptical rays.

The rays show no preference to any particular type of country, and do not appear to be deviated by mountains or other features. Rather, they cross over all other features. They behave as though they were superficial features, but their structure must include a third dimension which is small.

Whilst the rays are usually thought of as being bright features, this might possibly be a selective effect. For example, certain dark patches, a few miles across, are known within the crater Alphonsus,

and each spot contains a very small crater, of the order of a mile in diameter, situated about at its centre. The effect is most striking. Whether these patches are rays which are darker than the surrounding rocks is not known, since the characteristic ray-structure cannot be seen in the dark patches. On the other hand, there exist similar white patches around small craters elsewhere, and these white patches would seem to fall into the ray category. (It should be mentioned that, in Alphonsus, there are other small craters which are of the same dimensions as those mentioned above, but which are not associated with any dark patches. The same is, of course, generally true of small craters and white patches.)

To summarize the main types of ray, the following examples may be given:

(a) Thin, straight, and roughly radial (Aristillus type).
(b) Apparently curved (Copernicus type).
(c) Apparently structureless (many craterpits).

Visual examination has shown that the curved rays are very probably composed of linear elements, each element coming under class (a). Any of these types of ray may be symmetrical with respect to their parent crater, or may be asymmetrically disposed. Their albedos may vary.

One of the most interesting properties of the rays is their variation of intensity with the phase of the Moon. Relevant observations will be discussed in Section 10-5.

10-2 Special aspects of some ray systems

Since the rays show no preference to topography, but, like splashes, traverse mountains, valleys or seas without change of direction or of apparent nature, it seems probable that they were formed from above the surface, and not by forces which originated within the Moon. Furthermore, it seems probable that they were formed by the large-scale ejection of particles from certain craters. The same conclusions follow from the following observations.

Certain characteristics can be observed in the lunar ray-systems. One such characteristic is that the rays are often preferentially directed. The observed asymmetry of the Proclus rays provides a most striking example: the rays are not to be found on Palus Somnii. Urey (1956) has suggested tentatively that "the region of the Palus Somnii floated on the lava" and that "its surface has remained

darkened owing to heating and hydrogen sulphide from below". This is a very interesting suggestion. One would have to explain, however, why the rays are not seen on Mare Tranquillitatis, beyond

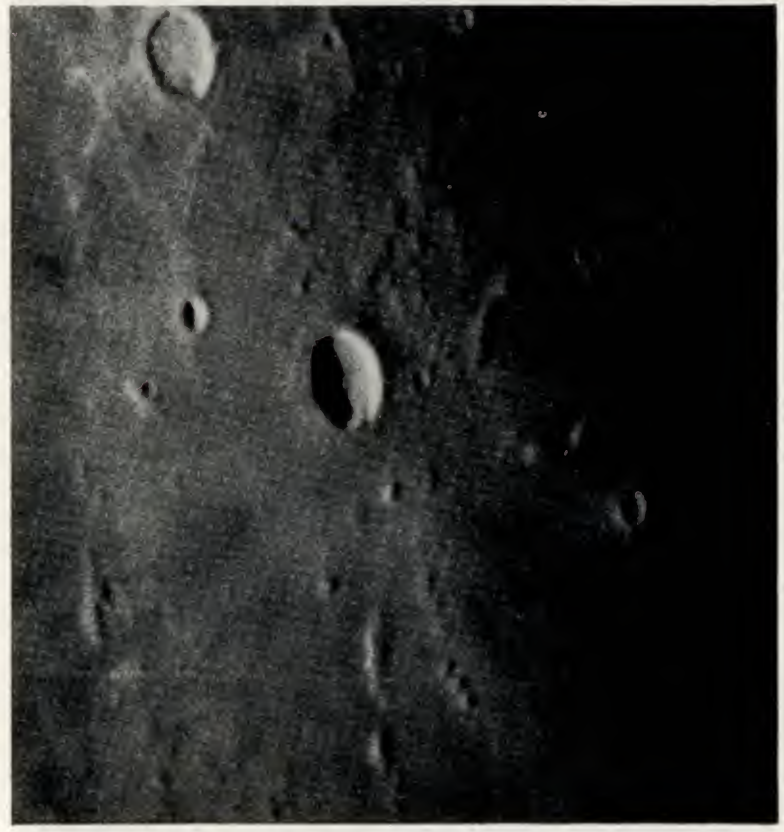

FIG. 10-2-1. Rays east of Kepler: evidence of particle ejections at small angles to the horizontal

the Marsh, and yet are visible on Mare Crisium at the same distance away from Proclus.*

Perhaps one way of overcoming this minor difficulty would be to assume that the two seas were of different ages. However, an

* In this connection, it is useful to study Mare Crisium from a point directly overhead: this can be accomplished by means of a Wright sphere. The technique is described by Alter and Roques (1955b) and is worth attention.

examination of the appropriate plates of the photographic atlas of Pickering (1903) indicates that the aversion of the Proclus rays from Palus Somnii is connected with the existence of certain high ridges which border Palus Somnii. These are intimately associated with the principal rays of Proclus. The ridges are apparently composed of the walls of many ruined craters. For example, a wall running roughly north–south situated some 50 km to the north-east of the centre of Proclus intercepts the rays which might, in the absence of this wall, have continued over Palus Somnii in that direction.

Further essentially similar cases are to be found in the ray-system of Kepler. About 50 km east of Kepler's centre there is a ridge which runs nearly north–south for about 15 km. East of this ridge there is a diverging zone, dark, because of the general paucity of rays in that region (see Fig. 10-2-1). Some rays do pass beyond the ridge, but the general absence of rays there is quite remarkable. Further to the north other ridges, the components being placed obliquely to the rays, contribute to a similar effect. In each of these cases, the rays of Kepler divide on reaching the ridge, or ridges, to leave a dark patch shaped like a truncated triangle. However, ridges to the north of Kepler which are oriented radially to the crater do not appear to have affected the normal spreading of the rays. These phenomena prompt one to suggest that the majority of the observed rays of Kepler were formed after ray-particles (whatever they might have been) were projected nearly radially from the crater and at very small angles to the horizontal. On these grounds, the ray particles impinged from above the surface, and sub-surface theories, such as Tomkins' (1906; 1907a; 1908) or Schwinner's (1943b), must be abandoned.

Darney (1934) has summarized some theories of ray formation and he, himself, believes that the rays might possibly be fractures in the lunar crust. This theory has been revived recently by Alter (1955c) who maintains that "the visible rays are either dust from gases that have escaped from the cracks or a staining of the rocks by such gases". Gold (1955a) supports the splash theory for the origin of the rays: he maintains that, assuming an impact origin for craters, the energy would always fall very short of that which would be required to produce fractures at the requisite distances. The reasons given by Alter do not convince the present author. Ray-triangles are a sure consequence of having more than two ray-systems overlapping, and the presence of craterlets at the intersection of rays is not

surprising in view of the fact that there is an abundance of bright craterlets elsewhere. It is true that the beads south of Stadius are intimately connected with the oval ray; Tomkins (1906) says that "many of the rays have minute craterlets along them"; but they can be explained as having been produced by "bombs" from Copernicus (see below). Alter gives no explanation for the ovals themselves but they also can be explained by the bomb theory (see 10-3). It seems, therefore, that the problem is not solved and that the suggestions of Alter and the author should be examined together.

Spurr (1948a) says that "there is evidence that the ash distribution was affected to an important degree by impeding minor crater eminences, behind which the ash was preferentially deposited . . .". Again, he writes (1948b), "surface ridges impeded the distribution of ash from . . . craters so markedly . . . that most of the ash did not drop directly on the surface . . .". It is well known that some rays appear to lie along wrinkle ridges. Tomkins (1908) wrote, "with a very low Sun, the sites of many of the rays can be seen as low ridges" and Pease (1924) pointed this out again. All these observations lend support to the above hypotheses. However, Lenham (1955a) in a paper on the rays of Copernicus, has cited cases of rays which pass, unchecked, over low mountain blocks. Possibly the fact that Copernicus is of a different order of size from Proclus and Kepler would help to explain any known differences on these lines.

Spurr (1948b) utilizes the horizontal carrying powers of heavy gases to explain the small angles at which certain ray-particles must have approached the surface but, even assuming more than one phase of ray-building (with and without a lunar atmosphere) the author finds it difficult to see why, in the first phase, the ash would not fall vertically. Yet, in spite of his observations of the impeding powers of ridges, Spurr (1948c) maintains that Palus Somnii is a fault block which sank after it "had been sapped by the liquid lava of Tranquillitatis". Ash from Proclus was not registered on Mare Tranquillitatis "because this was liquid", and Palus Somnii did not register the ash because this was in the process of being melted. To assume obstructive ridges in this case would seem to the author to be simpler and more acceptable. It is interesting to note that Gilbert (1893), in support of the splash hypothesis, wrote: "it explains the white crests of many grey craters, for peaks would intercept more than their *pro rata* of the horizontal shower".

In the case of Rosse, rays diverge from the crater in one direction only and there is a patch between the ringwall of Rosse and the place of commencement of the rays. The line of symmetry in the diverging rays lies almost parallel to the neighbouring Tycho rays. It would be extremely difficult to attribute such a non-symmetrical pattern to a volcanic upheaval in Rosse, and equally difficult to explain this preference to direction if the rays had originated explosively in Rosse during the impact of a meteorite.

Now Rinehart and White (1952a) conducted some interesting experiments with ultra-speed pellets. Their pellets were made to impinge with a plane at various angles. A photograph demonstrates how pulverized material can be preferentially directed during an impact at a small angle to the plane. Similar results have been obtained by Partridge and Vanfleet (1958). The author suggests that Rosse and its rays were produced when a tiny body was ejected from some explosion site (probably at Tycho) on the Moon's surface, the last part of the trajectory of this body being so inclined, and the velocity of the body being such that a momentum transfer of the kind described above operated during the impact. Had the same crater been produced by a very large-velocity meteorite it is thought that, whatever the angle of impact, the resulting ray system would have been fairly symmetrical. A patch untouched by rays just outside the crater ringwall would obviously be expected, and is probably analagous to the dark halo surrounding Tycho itself. Schindler (1912) has observed that "the dark Tycho rosette proves that no vertical expulsion has taken place . . .".

An alternative explanation that the dark haloes are due to the scattering of incident light by particles of rock flour or volcanic ash of the same order of size as the wavelength of light can be ruled out in view of the fact that, on this basis, the interiors of ray craters would also be dark. Furthermore, a size-analysis of rock flour by Buddhue (1948e) indicates that the majority of the finest particles produced by a collisional process would probably be at least 100 times too large to produce darkening. It is thought, therefore, that haloes are indeed further evidence for low ejections.

Spurr's (1948d) explanation of the unidirectional type of ray would appear to require a most marked asymmetry in the crater pit. In the oblique impact case, asymmetry would not necessarily be observed, as Rinehart and White have shown. The author suggests

that momentum was transferred from the small bomb which excavated Rosse to the crushed Moon-crust particles.

With much smaller bombs, producing crater beads which would not necessarily be resolvable, the linear nature of the elements which compose the rays of Copernicus might be explained. This hypothesis does not help to decide whether these craters which eject bombs are igneous or impact features, however: on either theory it is logical to assume that the integrated mass of ejected particles would be substantial.

If the ray-particles had suffered an explosive origin, then a spectrum of projection-angles would surely have resulted. The few rays beyond the ridge east of Kepler would thus be accounted for. Nevertheless, it is difficult to understand why the (visible) rays of the systems cited should have been produced by particles which were mostly projected at small angles to the horizontal.

10-3 Ray dynamics applied to the systems of Tycho and Copernicus

Mention has been made (10-1) of non-radial and elliptical rays. The rays from Tycho which pass over the southern limb, and the double-rays to the north-east of the same crater, passing Bullialdus, do not diverge from the centre of Tycho. Vand (1945a) believed that such rays form ellipses when seen in plan, and he thus supposed that matter was ejected in cones of small solid angles in such a manner that the axes of the cones were inclined at small angles to the horizontal. If α is a small angle of projection it may be shown that

$$\sin\alpha \approx \frac{2u}{1+\sqrt{(1+8u^2)}}, \qquad (10\text{-}3\text{-}1)$$

where u is defined by the relationship

$$u = \frac{\sin\alpha}{\cos 2\alpha} = \frac{b}{a}, \qquad (10\text{-}3\text{-}2)$$

a and b being the observed lengths of the axes of an ellipse. The velocity of projection may then be found from the equation

$$v = \sqrt{\left(\frac{gx}{\sin 2\alpha}\right)}, \qquad (10\text{-}3\text{-}3)$$

where x is the horizontal distance between the point of projection and the centre of the ellipse, and g is the acceleration due to gravity.

For Copernicus, Vand found $v = 1{\cdot}5$ km sec^{-1} and said that v was "much more for Tycho". The results should not be considered accurate, as the initial assumption stated that the range x must be small. Vand said that "the centre of the ellipse would be hit by

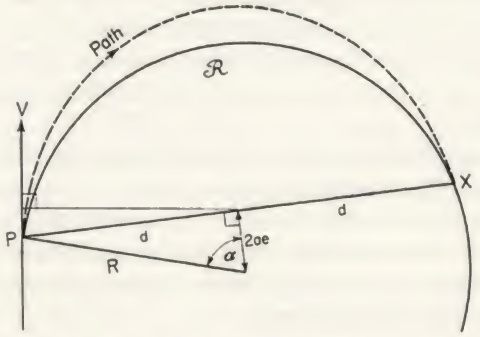

FIG. 10-3-1. Path of a projectile above Moon's surface

coarser debris of darker colour ... and the edges of the ellipse would be formed from gradually finer powder of lighter colour ...". However, he gave no explanation as to why this curious distribution of matter should prevail, and he did not explain the origin of the cones themselves.

The elliptical forms of Copernicus were plotted by Darney (1940), and although no theory such as Vand's was developed to explain the ellipses, Darney did notice that the major axes of the ellipses were directed towards Copernicus and he found, in a ray to the south-west of Copernicus, where the borders of the ellipse were composed of short elements, that each element was pointing towards Copernicus. Alter (1955c) has again pointed this out.

It is of interest to examine the exact dynamical behaviour of a ray-particle which is projected into a vacuum. A very neat method of finding the expression for the maximum arc-range (the range measured across the surface of the Moon) for a given angle of projection has been indicated by Loney (1950). It may be shown that

$$\alpha = \sin^{-1}\frac{d}{R}, \qquad (10\text{-}3\text{-}4)$$

where R is the radius of the Moon, $2d$ is the shortest distance between the points of projection, P, and re-intersection X, of the orbit with the

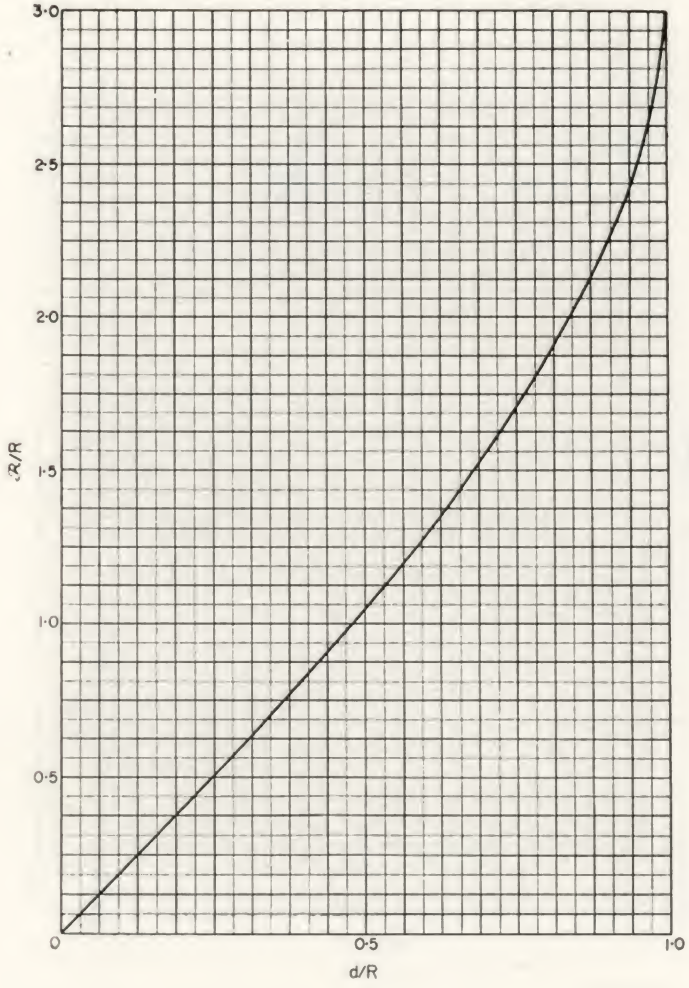

FIG. 10-3-2. The relationship between the arc-range $\mathscr{R}$ and the parameter d/R, as given by equation (10-3-4)

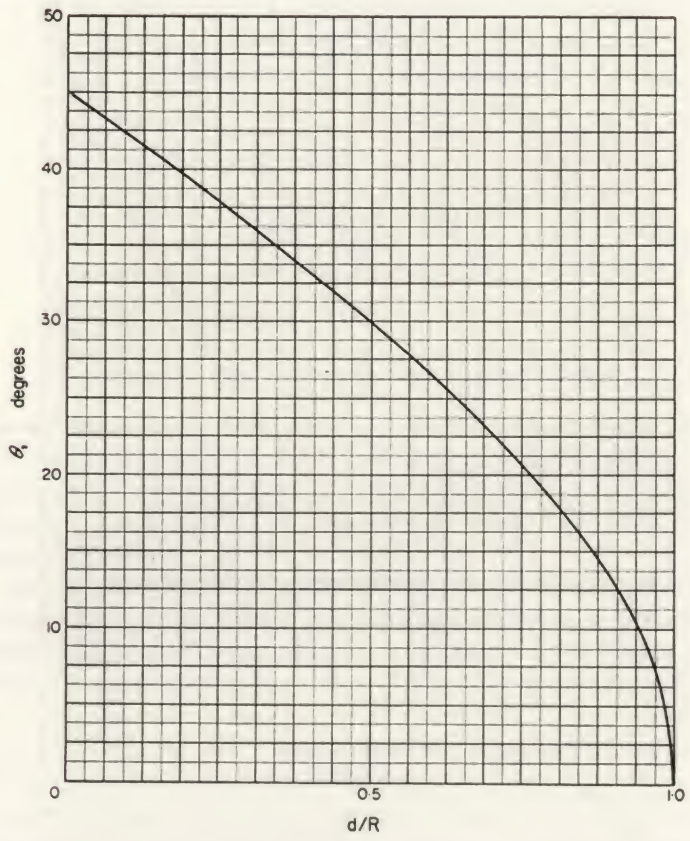

FIG. 10-3-3. The relationship between the angle of elevation, θ, and the parameter d/R, as given by equation (10-3-5)

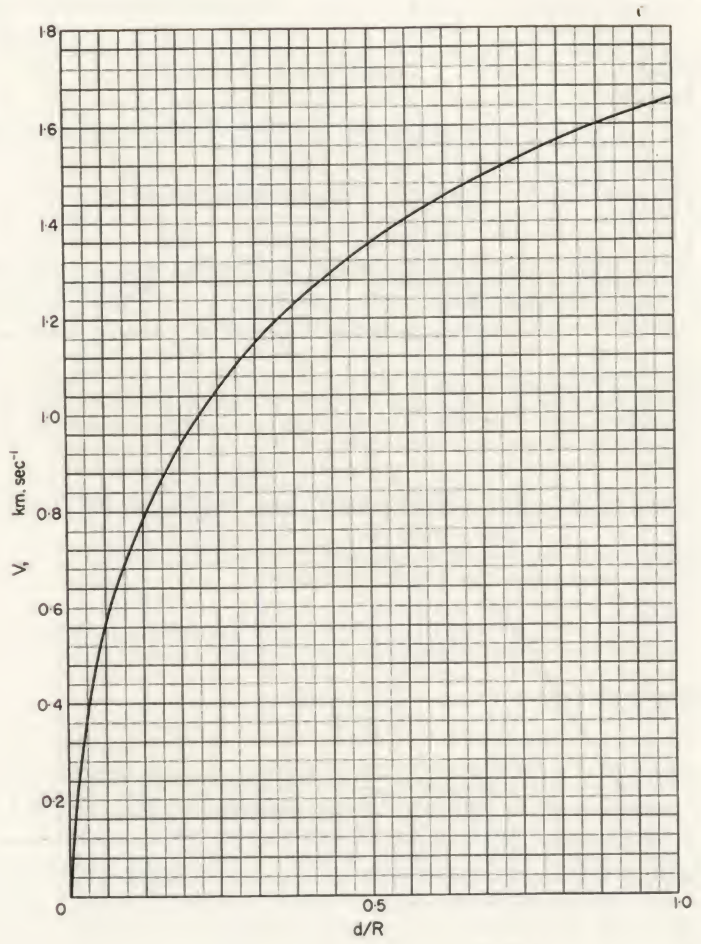

FIG. 10-3-4. The relationship between the velocity of projection, V, and the parameter d/R, as given by equation (10-3-6)

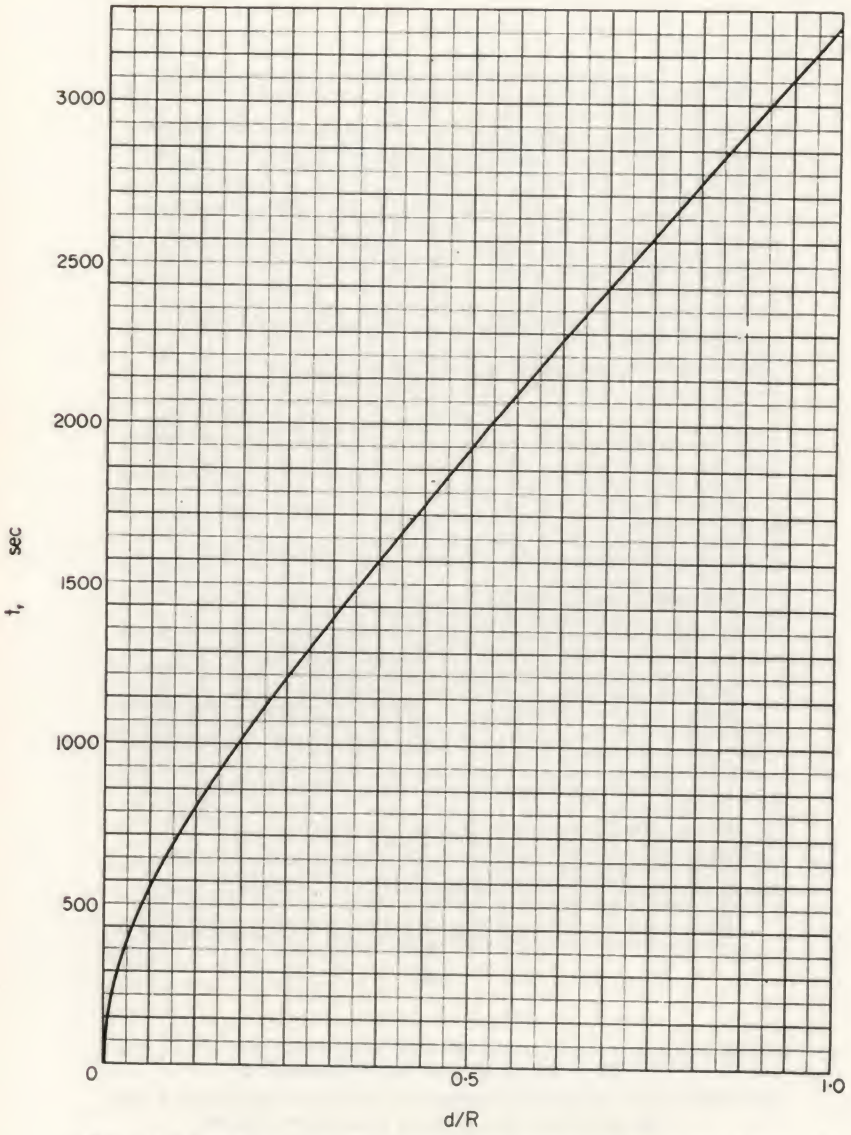

FIG. 10-3-5. The relationship between the time of flight, t, and the parameter d/R, as given by equation (10-3-7)

surface, and 2α the angle subtended at the centre of the Moon by the arc PX $= \mathscr{R}$ (see Fig. 10-3-1). It may be shown that the corresponding angle of elevation is given by

$$\theta = \tfrac{1}{2}\cos^{-1}\frac{d}{R}, \tag{10-3-5}$$

and the corresponding velocity of projection by

$$V^2 = 2.R^2.g\left[\frac{1}{R} - \frac{1}{R+d}\right], \tag{10-3-6}$$

where g is the gravitational acceleration at the surface. If G is Newton's constant of gravitation, $(g = (Gm)/R^2)$, and m is the mass of the Moon, the time of flight is given by

$$t = \frac{2a^{3/2}}{\sqrt{(Gm)}}\left[\pi - \left\{2\tan^{-1}\left(\sqrt{\left(\frac{1-e}{1+e}\right)}\cot\frac{\alpha}{2}\right) - \frac{e\sin\alpha\sqrt{(1-e^2)}}{1-e\cos\alpha}\right\}\right]. \tag{10-3-7}$$

Here, a is the semi-major axis of the elliptical orbit and is given by

$$a = \frac{R+d}{2}. \tag{10-3-8}$$

The eccentricity e of the ellipse is given by

$$e = \frac{R.\cos\alpha}{R+d}. \tag{10-3-9}$$

The maximum possible range is found by putting $d = R$ in equation (10-3-4). This gives an "infinite" range, and, applying the same condition to equations (10-3-5) and (10-3-6), respectively, it is seen that the corresponding angle of projection is 0°, and the velocity is $\sqrt{Rg}$. The orbit is then circular. In practice a circular orbit would be impossible for a projectile launched from a point on the surface, since $\theta = 0°$ and hence the projectile would soon encounter obstacles. From equations (10-3-4) and (10-3-5) it is obvious that the smaller the angle θ, the greater will be the range α.

Equations (10-3-4), (10-3-5), (10-3-6) and (10-3-7) have been used to construct the graphs shown in Figs. 10-3-2, 10-3-3, 10-3-4 and 10-3-5, respectively. The same variable, namely d/R, has been used with the same scale for the abscissae of all of these graphs, so

that it becomes easy to relate the ranges, angles of projection, velocities of projection, and corresponding times of flight for any value of one of the variables.

Various estimates have been made of the maximum length of the Tycho rays. Wright (1935a) said that they had been traced for 2400 km. He wrote, "... for this distance an initial velocity of 1·48 km sec^{-1} is required and an elevation of 26 degrees". These figures may be confirmed from Figs. 10-3-2, 10-3-3, and 10-3-4, by putting the arc-range $\mathscr{R} = 1738$ km. Hacker and Stewart (1935b) estimate the maximum length of the Tycho rays as 2090 km and a figure of 1300 km has been used by Vand (1945a). Some writers have undoubtedly involved the ray which crosses Mare Serenitatis in the neighbourhood of Bessel, but the author believes that this ray does not belong to the Tycho system, and that 1900 km represents the arc-length of the longest ray. It follows from Figs. 10-3-2, 10-3-3, 10-3-4 and 10-3-5 that, if this is to represent a maximum range, then the angle of projection of the particle which produced the end of the ray must have been nearly 30 degrees, the velocity of projection 1·37 km sec^{-1}, and the time of flight nearly 33 min. For other angles of projection, the completion of the ray would still have been possible, of course, but larger velocities would have been required. The paths of particles would have been ellipses in all cases, the far foci having been coincident and full.

10-4. Relative and absolute times of formation

Excepting the phenomenon of ray-stoppage by ridges, discussed in (10-2), even the longest rays appear to cross over all other features. This would suggest that the rays were comparatively young features. It does not follow, however, that they indicate the most recent form of activity on the Moon. Erosion due to the continual impacts of very small meteorites and the influences of solar energy, among which may be mentioned the darkening effect of ultraviolet radiation upon perfect minerals, must be slowly influencing the rays as well as all other parts of the Moon's surface. Rays will therefore be most prominent when they are first formed, and will gradually fade over millions of years, and eventually disappear. At the same time, their parent craters will be subject to essentially the same erosional forces.

Craters which have suffered very much erosion rarely display any rays and are never associated with prominent ray-systems. Tycho—

the most famous ray-crater—looks comparatively young: its depth–diameter ratio is fairly large for a crater of its diameter-class, and its walls and central mountains are fairly sharply cut. However, crustal movements must have occurred after the formation of Tycho, as the walls have been distorted and the author has observed a series of ridges actually passing inside the walls. Since lateral crustal displacements would probably be small in comparison with the widths of long rays, it may be supposed that the rays were formed either before, simultaneously with, or after, such movements. This observation does not contradict the impact theory of the origin of the rays.

The method of ejection of ray particles might follow two patterns. On an igneous theory, ash might be ejected from the vent at the summit of a central mountain—see, for example, Spurr (1948) or Moore (1946)—from vents in the ringwalls of craters, or, possibly, from crater floors in an active state. A description of summit craters has been given by Moore (1953a). The exact mechanism of an ash-explosion is not certain. Verhoogen (1951) believes that, provided the number of gas-bubbles n in a terrestrial magma is connected with the temperature T_0 and the depth of origin, h, by the relationship

$$n^{4/3} > \frac{8{\cdot}2 \times 10^7}{T_0 h}, \qquad (10\text{-}4\text{-}1)$$

then ash will be formed. He wrote, "A magma containing little water, but which is strongly oversaturated (due, for instance, to a drastic reduction of the external pressure), might vesiculate faster than a water-rich magma which is only moderately removed from its equilibrium state." Another factor which influences vesiculation is crystallization of a magma, nucleation occurring more readily in the presence of this phenomenon.

Hence it seems as if a sudden reduction in the surrounding pressure, together with the presence of rapid crystallization, may possibly offset the effect of small equivalent values of the variable h in equation (10-4-1), to allow ash explosions to operate even only just beneath the surface of the Moon.

On an impact theory, rock particles—pulverized or of appreciable size—would be ejected during the explosion. Now terrestrial volcanoes have been known to eject even large particles with explosive velocities and in horizontal directions. Wright (1935a) said "An

initial velocity of ejection from terrestrial volcanoes exceeding 2 km sec^{-1} has been deduced from observations of the volcano Cotopaxi. On the moon the materials ejected from a lunar crater are scattered far and wide, whereas on the earth the greater part of the ejected rock fragments and blocks fall near and into the crater orifice. As a result of this dispersion the lunar craters are cleaned out as a rule . . .". Referring to the same Ecuador volcano, Marshall (1943a) quotes 0·92 miles sec^{-1} (1·47 km sec^{-1}) as the maximum observed ejection velocity. Hacker and Stewart (1935b) wrote, "in the case of Lassen Peak, California (May, 1915) . . . horizontal blasts through the north-east side of the inclosing cone hurtled blocks of rock for more than four miles". So it is not easy to decide, on dynamical considerations alone, which explosive process—igneous or impact—was in operation. However, if ash were ejected explosively from a summit crater, one would expect to observe the streamers pointing towards that crater, whereas, during a collisional process, matter would be projected from no clear focus.

Pickering (1892) pointed out that rays generally come from bright craters which "rarely exceed one mile in diameter and are frequently much less". Of the rays of Tycho, he said they "do not point exactly in the direction of the centre of the great crater, but towards a multitude of very minute craters . . . upon its south-eastern and northern rims". Pickering said that the parallel Tycho–Bullialdus rays ". . . must . . . not be considered as two streaks, but as two series of streaks, the components of which are placed end to end", and he maintained that these short streaks were never longer than about 15–80 km.

Whilst there can be little doubt that ray-elements often originate in craters, one must treat warily the proposition that the rays of Tycho originate in its ringwall craters. Firstly, ray-particles originating from the central regions of the crater might be trapped by such ringwall craters, thus rendering them brighter and more conspicuous than other craters of the same size but situated elsewhere. (The same might be true of the much discussed "on-the-ray" craters.) Another example of essentially the same phenomenon has been given by Billerbeck-Gentz (1943c) who said that the Tycho ray between the Altai scarp and Rosse consisted of four short elements, each element emerging from a crater, and the elements lying along lines of hills or of low mounds. Secondly, how might we explain the fact

that such wall-craters dispose of their ray particles in only one direction, which is always away from the main crater? On these arguments, the theory that the rays are formed by particles which are projected from the circle of confusion created by the impact of a large meteorite would seem to be more acceptable. Yet, if it could be shown that ray-elements were always directed towards the centres of craters with central mountains, the ash-producing mechanism mentioned above would seem to be equally worthy of consideration.

An examination of the individual ray-elements which form the rays of Copernicus indicated that the floor of the crater (that is, the sunken portions of the crater of annular shape) was a more probable source of ejectmenta than was the centre. If particles had been ejected from the annular floors of craters, then the roughly elliptical ray-forms of Darney, Vand and Alter would very probably have been produced when the particles had reintersected the lunar surface. Such ellipses would have dark centres, whilst ray craters without central mountains would not be expected to exhibit elliptical rays with dark centres.

Urey (1952b) has raised the question of possible circum-lunar rays. He suggests that the broad ray running from the south-east ringwall of Tycho, over the south limb of the Moon, was formed in consequence of the action of particles which had travelled once around the Moon. The observed displacement from the centre of Tycho would be a consequence of the axial rotation of the Moon, and would enable an estimate to be made of the time of formation of the ray. Such behaviour would be dynamically possible if certain assumptions were made. These are: (a) the angle of projection was at zero degrees to the horizontal; (b) the explosion which produced the rays was centred at some distance above the lunar surface (in order that the particles might not have been stopped by the mountains); (c) the velocity of projection was greater than or equal to the local circular velocity but less than the local velocity of escape, and (d) the particles were slowed down by some resistive medium in such a manner that they would impinge with the Moon's surface at just the appropriate times. There are no serious objections to the first three of these conditions, but the difficulty which would be involved in accepting condition (d) is surely very great. Another reason for believing that the suggested process is very improbable is that the ray across Mare

Serenitatis (which is sometimes attributed to Tycho) can be seen, on suitable photographs of full Moon, to make a perceptible angle with the Tycho rays in its neighbourhood, and there is every indication that the Tycho rays dwindle out just before Mare Serenitatis is reached.

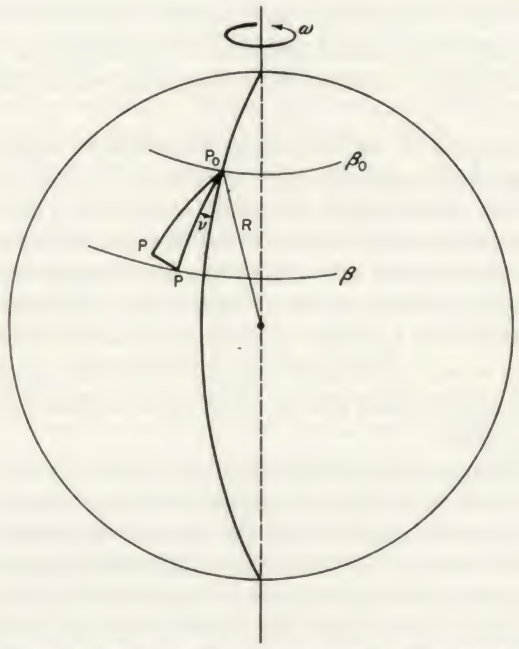

FIG. 10-4-1. The displacement of rays on a rotating Moon
(For the left-hand P read P′)

There can be little doubt that the rotation of the Moon has influenced the observed paths of the rays. The deviation of a ray of type (a) (see 10-1) from a great circle would be a measure of the period of the Moon's axial rotation at the time when the ray was being formed, and hence an estimate of the "absolute" time of formation of the ray may in principle be sought.

In Fig. 10-4-1 let a particle be projected, at time 0, from a point P_0, at latitude β_0, along a great circle P_0P including an angle v with the meridian through P_0. Let the particle arrive at P′ at time t. Suppose, at first, that the points P_0, P, and P′ are so close to one another that this part of the Moon's surface may be considered as plane. Then, during the interval of time t, P will have moved along its parallel of latitude, β, through a distance $\omega R(\cos\beta - \cos\beta_0)t$ relative to P_0, where ω and R are the angular velocity and radius of the Moon, respectively. The apparent deviation, δ (= PP′) of the particle's orbit from its original position, for an observer moving with P, may then be defined as

$$\delta \approx \omega R(\cos\beta - \cos\beta_0)t\cos v. \qquad (10\text{-}4\text{-}2)$$

This approximation holds for the curved surface even if the difference of the latitudes $(\beta - \beta_0)$ is appreciable, provided v is small: that is, for motion close to a meridian.

If, therefore, the term in v is written as unity, δ will be large when β_0 is large and β is small. Tycho is the ray crater which has rays approximating most closely to these conditions: β_0 is 42° and β may be put equal to 0. If the rays were formed when the Moon was rotating at the present rate, ω may be put equal to 0·00958 radian per hour, t may be estimated to be 0·46 hr, by the use of the graphs of Figs. 10-3-2 and 10-3-5, and these values given $\delta \approx 2$ km.

Now if the rays had been continuous and only of this order of width, it would have been possible to measure the displacements δ, in the most favourable cases. As it is, the long rays are always considerably wider than 2 km.

If the Moon had been closer to the Earth in the past, and always a synchronous satellite, ω would have been larger, and larger displacements would have resulted, but unfortunately these would never have been large enough to enable one to conclude that the rays were formed recently, on a time-scale having its origin at the birth of the Moon. For example, if a displacement of $\delta = 20$ km would be just detectable, equation (10-4-2) would require that ω be increased by a factor of 10. This would bring the Moon, assumed always a synchronous satellite, to within a distance of the order of 100,000 km from the Earth. The rays were probably formed when the Moon was as least as far away as this.

There is, however, another important test of the age of the rays: if it is assumed that the particles were projected in a plane of given azimuth at all angles of elevation, it follows immediately that, on a rotating Moon, there would in general be two branches to a ray. For a given velocity of projection, there is an angle of projection which gives a maximum range. If this angle be either increased or decreased with the velocity kept constant, the projectiles will fall short of the

maximum range. However, in the first instance the time of flight will be greater than in the second instance and, therefore, because of the rotation of the Moon, particles projected into the higher series of orbits will intersect the surface in a curve which lies to the east of the ray formed by particles shot into lower orbits. L. A. Giamboni (1949) applied this theory to the rays of Tycho. He varied the rotational period of the Moon and the velocity of ejection of particles, and computed the resulting surface loci of ray-particles until he was able to match the observed ray-patterns. Giamboni concluded that, when the rays of Tycho were formed, the siderial period of the Moon assumed a value of between 0·5 and 6·8 days.

The lower limit of the rotational period, inserted in equation (10-4-2), gives $\delta \sim 100$ km. A 100 km displacement of the ray in question should be detectable but might be masked by the fact that the "bowing" of the ray could take place uniformly along its length. The upper limit of 6·8 days gives $\delta \sim 10$ km—a displacement too small to be detected.

10-5. On the discrete nature of the rays

The fact that rays near to the limb are conspicuous both when the observer's line of sight and the direction of illumination are parallel (full Moon), and when these lines are perpendicular (Moon's disk half illuminated), was pointed out by MacDonald (1945b). Pickering (1907b) wrote "no matter what part of the surface they may be situated ... they are invisible only when the source of illumination is less than about 10 degrees above their horizon" and "it is only the angle of incidence (of light) which is of consequence". In agreement with this, Lenham (1955a) has remarked that "the major rays are seen only when 8 degrees or 9 degrees from the terminator".

In an attempt to reproduce in the laboratory the brightness-behaviour of the lunar rays, Buell and Stewart (1932) prepared a surface consisting of particles of basalt 0·05 inches in size, interspersed with pulverized basalt. However, they do not seem to have tested the limb effects, and it would appear that reproducible effects would not have been obtained in these cases, so that their model must be rejected.

The author constructed two geometrical models, one representing a spherical surface of radius R, coated uniformly with hemispherical

protuberances, and the other representing the same surface coated with hemispherical concavities. These hemispherical lumps and pits were taken to have radii which were small in comparison with R, but large in comparison with the wavelength of light. It was found that, although superposition of these models gave the best representation of the observed facts, neither model by itself gave intensity variations which accorded with those known for the lunar rays.

A detailed investigation into the intensity-phase effect over luna-base, lunarite, and ray-regions was performed by Schoenberg (1925; 1929). He found that the brightness variability of the central disk regions—continents or maria—could be explained by assuming a surface thickly peppered with hemispherical depressions, the regions between these depressions being convex upwards. "It follows ..." he wrote "that no liquid, fluid, or dust-carrying atmosphere would prevail, because in these cases the holes would be filled in." However, the optical properties of an atmosphere of dust have not yet been evaluated. For the rays, Schoenberg says that, as for bright craterlets, the holes must be of such a form that light can penetrate only at very small incident angles. Another way seen by Schoenberg to explain the observed facts would be to assume a layer of loose stones, but he rejects this hypothesis as being improbable.

Pickering (1907b) considered that the rays were due either to a substance of larger reflectivity than the general surface, situated at the bottoms of cracks, or to pellets lying upon the (darker) surface. "These", he concluded, "are apparently the only possible geometrical solutions of the problem". Pickering's first hypothesis, like Buell's and Stewart's, suffers in that it does not explain limb rays, so that we are left with a combination of pellets and cup-shaped hollows to be the most plausible form of reflecting surface in ray regions.

It is important to ask what the discrete nature of the rays would be on the postulated ejection process. A small body moving at $\sim 0{\cdot}5$ km sec^{-1} would certainly be expected to produce a cup-shaped crater. Crushed rocks would be thrown out, and these particles, having much smaller velocities, would not be expected to form depressions on a surface having appreciable tensile strength. This would suggest that the rays consist of hollows radiating from which, often in one direction only, are many particles of irregular dimensions but of much smaller diameters than their parent hollows. The difficulty of testing such a model in the laboratory will be apparent

when it is realized that the real limb of the Moon is not of uniform curvature: ray-forming bombs would be expected to hit the faces of mountains and hence, in limb regions, we would be looking directly into the hollows more often than a simple model would suggest. The volumes of the hollows would depend upon the energies of the bombs. The maximum particle size of the ejected crustal material would depend upon the size of the hollow from which it came. As Steavenson (1945c) has remarked, the ray particles still need not necessarily be dust; they could be "quite sizeable masses of rock".

If, as seems plausible, ray craters are among the most recent, then the relatively large albedos of the rays might be explained by assuming that the freshly upturned rocks which line the bomb-crater bottoms and of which the ejected ray-particles, spreading out from these bomb craters, are supposedly composed, have not been exposed for a sufficient length of time to the darkening effect of high-frequency solar radiation, described by Stair and Johnston (1953b).

Before the problem can be investigated much further, it is suggested that it will be necessary to obtain the photometric and polarization curves not of integrated ray systems but of individual rays, and in such a manner that the rays which are chosen lie in regions where steep slopes are at a minimum. Graff (1948f) has already listed some useful photometric measurements of five rays of Tycho.

10-6. Dark bands

Like the rays, dark bands may in some cases be found running radially up the brightly illuminated interior slopes of the crater-walls. These regions appear darker than they actually are as the result of their contrast with adjacent regions (rays, for example) of larger average albedo. Wilkins and Moore (1955e), using the 33-in. refractor at Meudon, detected "fine structure" in the bands of Aristarchus, and the author, under very good conditions at the Pic-du-Midi, verified that the bands were not linear features, but simply patches of darker material set in a more highly reflective background. The more highly reflective parts were thought to be low hills. These would be brighter than the depressed, darker patches because the hills would have intercepted ray-particles, as discussed in 10-2.

Dark bands are not necessarily radial; circumferential bands seem to be associated with the terraces of the inner walls of craters.

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CHAPTER 11

The Grid System and Lattice Patterns

11-1. **Linear features**

When the conditions of observation surpass moderate limits, it becomes apparent that the rays are not the only linear features on the Moon's surface. Resolution of the detailed structure of the mountain-chains and general structure of the continents reveals a network of linear formations. These formations may be classed very broadly as (a) valleys and (b) ridges. The entire system of linear features may be called the *lunar grid system*, and different components of this system may be said to belong to different *families*. It may be desirable to distinguish two types of family: the radial type (see 11-2) and the parallel type (see 11-3).

The valleys themselves fall into three distinct classes. One may be called the Schroeter type, since it takes the form of Schroeter's Valley (also called Schroeter's Canyon or the Herodotus Rille). Another class of valley may be grouped under the Alpine type, and the third grouping may be said to be of the Rheita-type.

The Schroeter type of valley (Fig. 11-1-1) takes simply the form of a rille (see Chapter 12) and is not generally linear, although there are exceptions which will be mentioned in (11-3).

The Alpine Valley forms a vast, cigar-shaped breach through the lunar Alps (Fig. 11-1-2). It is of the order of 150 km in length, and is some 8 km from edge to edge at its widest point. Towering above the dark, generally apparently flat, floor are impressive scarps, but in reality they probably have gentle slopes. Kuiper (1954a) believes that there is a transverse fault* about half way along the Valley, and he attributes the Valley itself to ground movements in the Moon's outer shells. The valleys in the regions around the centre of the disk

* This feature has been known for a long time, but the author is not clear as to its exact nature.

will be classed with the Alpine Valley, even though they may not be of similar origin. These valleys are all much narrower than the Alpine Valley, and they look like grooves. All of these Alpine-type valleys are characterized by their straightness and by their preference to mountainous regions.

Different yet again is the Rheita Valley type. The Rheita Valley (see Fig. 11-1-3) might give to the casual observer the impression of its being a long, shallow trough with a sharp bend in it, becoming narrower and deeper after the bed. In actual fact it is, in the main, a complex chain of craters. Other valleys of this type are common, and are usually called crater chains.

Ridges, it would appear, are essentially of one type: they are striations of the ringwalls of craters or maria. (The word "ridge" should be taken here to mean a linear elevation of mountainous characteristics: these features cannot be described as "mountain chains" since this name already applies to the grand chains). It is sometimes difficult to distinguish between an Alpine-type valley and two close, parallel ridges.

11-2. The system radial to Mare Imbrium

It will be seen from a comparison of Figs. 11-1-1, 11-1-2, 11-1-3 and 11-2-1 that, whilst many of the valleys around Ptolemaeus fall into the Alpine-type of grouping, they appear to differ considerably when details are studied.

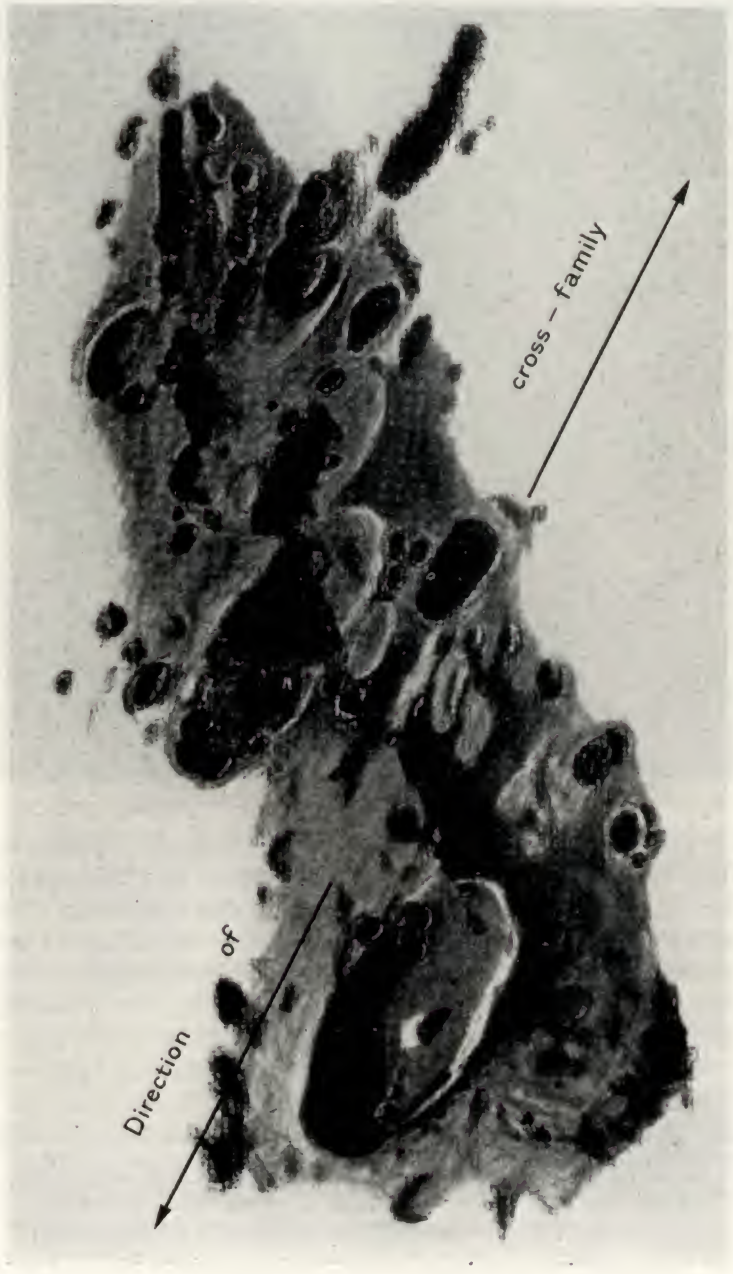
Two plausible means of valley formation which have been suggested are, respectively, that the Ptolemaeus valleys were caused by faulting, and that they were indentations produced during glancing blows from extra-lunar bodies.

The former mechanism was suspected by Tomkins (1907) and has been revived more recently by Spurr (1944). The dimensions of the lunar valleys are, however, quite unlike those of terrestrial rift valleys (1948c), and it is not easy to explain the relative orientation of the lunar valleys on this hypothesis. Again, no rift valleys would cut through only the peaks of mountains to leave the ground-level between the peaks undisplaced. The actual mechanism of rift valley production is, however, not understood: Jeffreys (1952a) has discussed three theories briefly.

Steavenson (1919a) examined the valleys and stressed that they must have had a common origin because of their similar breadths

FIG. 11-1-1. A rille near to Herodotus, sometimes called "Schroeter's Valley"

FIG. 11-1-2. The Alpine Valley (top, centre): a vast breach in the lunar Alps



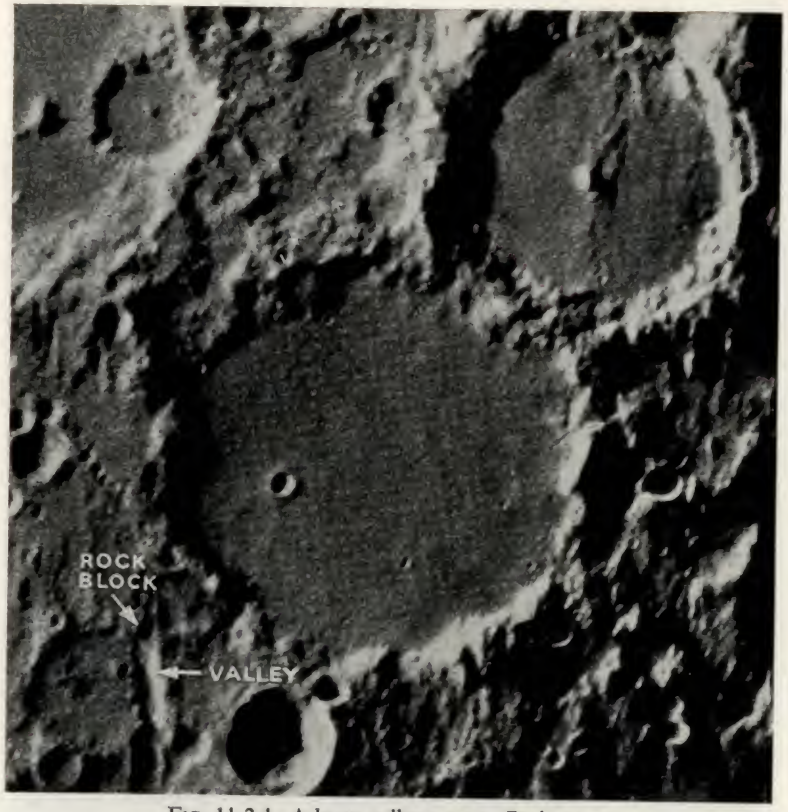


FIG. 11-2-1. A large valley near to Ptolemaeus

and general appearance, and because of the tendency to parallelism which they display. In fact, he might well have said "tendency to convergence". Steavenson also pointed out that, since most of the valleys were later than the craters, they were not associated with crater-forming activity and he suggested the grazing-impact hypothesis, which was supported by Davidson (1919b). More recently, this hypothesis has been modified by Baldwin (1942; 1943) and by Urey (1952c) both of whom have found a considerable amount of support for the ideas of Gilbert (1893b). Gilbert supposed that a huge explosion in Mare Imbrium had ejected materials in all directions

FIG. 11-1-3. The Rheita Valley: a famous crater-chain and fault. Carbon sketch by Fielder, 1956 June 12. (Pic-du-Midi Observatory, 60-cm refractor x 1026)

and that "... the lunar furrows were really formed by the forceful movement of a hard body ... controlled by its own inertia".

The author scrutinized the Mount Wilson photographs of the Ptolemaeus regions with the aid of a magnifying lens, and a study of the grooves in these regions revealed that huge, isolated blocks were often to be found near to their ends.

Kuiper (1954a) has pointed out the most prominent case. It is a wide groove, *a*, just west of Herschel, of which the southern end is terminated by an irregular elongated rock block some 10 km in length but only half as broad. The valley itself—which has been identified in Fig. 11-2-1—varies considerably in width, but its width is always comparable with the dimensions of the block of rock. Such irregularities would be expected if the ploughing body had imparted momenta to other blocks in its path.

However, as Kuiper has suggested, this is by no means the only case in which there is an association between grooves and blocks. Fifty kilometres to the east of the easternmost ramparts of Ptolemaeus there is a short, narrow valley *b*, which might or might not* have an associated coaxial block at its south end. The major axis of the block is co-axial with the valley. Located in the south-west ringwall of Alphonsus is a deep groove, *c*, which has towards its southern end two boulders which each appear to be roughly spherical, but which lie closely together, such that the line joining their centres lies parallel to, and in, the valley. It appears possible that, if these boulders were not wholly responsible for cutting the groove, they were once attached to the larger elongated block which can be seen still further to the south. Just west of the west ringwall of Alphonsus there is a tapering irregular groove, *d*, with a block elongated in the direction of the groove and very slightly removed from its southern end. East of Flammarion there are numerous examples of short valleys. One of these, *e*, about thirty miles south of Mösting, has an elongated block placed diagonally across its south end, but has a smaller elongated block, pointing along the groove, at its northern end. Other striking cases of elongated blocks—this time somewhat removed from the ends of their associated grooves—are to be found just to the south-east of Flammarion. One of these will be denoted by *f*.

It is seen from these examples that not only is there a clearly defined association between blocks and grooves but, also, there is a marked

* This is a revision of the author's (1955) previous statement.

tendency for the blocks to be elongated and to be so oriented that their major axes are generally roughly coincident with the axes of their associated grooves.

If it is to be assumed that the valleys which are oriented radially with respect to Mare Imbrium were produced when large chunks of material were projected nearly tangentially from some common site on the Moon, then clearly this projection site must be located in Mare Imbrium. On this basis, the velocity of a projectile at the commencement of valley formation must deviate little from the local circular velocity. Thus, the orientation of the blocks can only mean that either the projectiles themselves were of the greatest dimensions in their original directions of travel or they became elongated, for some reason, during the gouging out process.

Such a relationship is to be found between dimensions and direction of travel in a drop projected from the ringwall of a liqui-crater (1908b) and this might suggest that the collision in Mare Imbrium possessed some essentials of a hydrodynamical process. However, the time of travel of a projectile launched from Mare Imbrium would be of the order of 10 min, and the cooling of a molten rock droplet of the requisite mass over such a period is insufficient to secure solidity throughout. Furthermore, the droplet clearly could not have been liquid at the time of collision, for in that case it would not remain. Thus, it is necessary to examine some other mechanism in order to explain the observed elongations in the directions of travel.

At the velocities involved, it is likely that fracture of the fragment would commence close to its leading surface (1954b). The tendency to fracture would be offset, to some extent, by the large pressures and temperatures involved and would be replaced by a tendency to flow plastically, but these effects would last only for a short time since the velocity decreases rapidly as time elapses. Davidson (1919b) said that the projectile "would not lose much of its surface through fusion, owing to the short time of flight".

In order to examine this idea quantitatively, one may equate the kinetic energy, $\frac{1}{2}mv^2$, of the colliding body to its thermal energy, given by $\frac{3}{2}kT(mN/\mu)$ where k is Boltzmann's constant ($1{\cdot}33\times10^{-16}$ c.g.s. units), N is Avogadro's number (6×10^{23}), μ is the mean atomic weight of the substances which are in collision, and T is the absolute temperature which is developed. It follows that, for a given velocity v measured in km sec^{-1},

$$v = \sqrt{\left(\frac{T}{40\mu}\right)}. \tag{11-2-1}$$

With $T = 1500°\text{K}$, and $\mu = 30$, equation (11-2-1) yields $v = 1{\cdot}1$ km sec^{-1}. This means that the forces acting along the shear surfaces would cause parts of both the lunar crust and the fragment to be raised to temperatures in excess of the melting points of most rocks for velocities greater than about $1{\cdot}1$ km sec^{-1}. However, the velocity of the moving body would be reduced to <1 km sec^{-1} in such a short time that heating would be relatively unimportant. It is doubtful whether the shearing action previously considered by the author (1955) could explain the observed forms of the projectiles.

Nevertheless, it is important to ask if the mechanism of groove-formation which has been suggested above is physically plausible.

The equation of motion of a projectile of mass m and radius r, moving with velocity v through a resistive medium may be put in the form

$$m\left(-v.\frac{\mathrm{d}v}{\mathrm{d}s}\right) = \pi r^2(\alpha + \beta.v^2), \tag{11-2-2}$$

where α and β are constants specific to the medium. Let V be the velocity of the projectile at the commencement of valley-formation, and v its velocity at the end of valley-formation. Then,

$$m\int_v^V \frac{v.\mathrm{d}v}{\alpha + \beta v^2} = \pi r^2 \int_0^s \mathrm{d}s.$$

Hence,

$$s = \frac{2r\rho}{3\beta}.2{\cdot}3026\log_{10}\left(\frac{\alpha + \beta V^2}{\alpha + \beta v^2}\right), \tag{11-2-3}$$

where ρ is the density of the projectile.

One may write

$$s = \frac{Cr\rho}{\beta}.\log_{10}\left(\frac{\alpha + \beta V^2}{\alpha + \beta v^2}\right), \tag{11-2-4}$$

where C is a constant which does not depend on the medium which is being penetrated. The constant for a particular medium may be evaluated experimentally in the following manner. From equation (11-2-4), if two projectiles commence penetration at different

initial velocities and penetrate to distances s and s' respectively,

$$\frac{s}{s'} = \frac{\log(1 + (\beta/\alpha)V^2)}{\log(1 + (\beta/\alpha)V'^2)} . \qquad (11\text{-}2\text{-}5)$$

The value of β/α which is found from this equation may then be used in

$$\beta = \frac{Cr\rho}{s} \log_{10}\left(1 + \frac{\beta}{\alpha} V^2\right), \qquad (11\text{-}2\text{-}6)$$

which follows from equation (11-2-4), in order to evaluate β. Hence, knowing the ratio β/α, α may be found. The constant C may then be found from equation (11-2-6). Davidson (1919b) found $C \simeq 157$, and this value will be adopted here.

Now equation (11-2-4), which was developed by Didion (1860), and which, in principle, may be applied to an investigation of the formation of any lunar grooves that may have been gouged out by the ploughing action of projectiles, is of little use for application to specific cases, owing to the fact that so many of the quantities in it are uncertain. An attempt was therefore made to minimize such uncertainties.

For all the grooves in the Ptolemaeus region, described above, the initial velocity V can be considered to have the same value. Thus, the ratio of the energy of a (spherical) projectile to its projected area would be proportional to its radius. This means that, under the limitations of this simple consideration, the wider grooves would be expected to be the longer. The evidence indicates that the final velocity v must be taken as zero. Hence it is seen from equation (11-2-4) that the ratio s/r would be expected to be constant. Direct comparisons on the photographs produced the following rough results for this ratio:

TABLE 11-2-1

Valley	*a*	*b*	*c*	*d*	*e*	*f*	Average
$s/2r$	8	—	5 or 10	9	6	6	~8
s/b	4	—	3 or 6	4·5	2	2·7	~4
$b/2r$	2	—	1·7	2	3	2·2	~2

The average value of s/r was found to be about 16 and this was used in conjunction with $v = 0$ and $V = 1{\cdot}68$ km sec^{-1} (circular velocity).

In Table 11-2-1, b represents the breadth of a valley, which has been taken to be the distance between the highest parts of its bordering walls. It is seen that the ratio of the breadth of a valley to the breadth of the associated block is roughly constant and equal to two.

Now the constants α and β are specific to the Moon's crustal materials and are not known. Didion (1860) gave $\alpha = 4{\cdot}35 \times 10^5$ and $\beta = 88$ for sand mixed with gravel. For concrete, Baldwin gave $\alpha = 4{\cdot}34 \times 10^7$ and $\beta = 40{\cdot}5$ and said (1949a) that the lunar materials would offer a resistance "many times less than solid rock, although perhaps higher than would be developed by sand and gravel". Urey (1952c) remarked that ". . . moist materials offer much less resistance to projectiles and hence substantially higher values than the minimum and somewhat less than the maximum are likely to apply to the Moon's surface". Now α is the less critical of the two constants, and this was therefore chosen to be 10^7. The more critical constant β was calculated for a projectile of density 3 g cm^{-3}, by writing equation (11-2-4) in the form

$$\frac{3C\rho}{2\beta} \log_{10}\left(\frac{\alpha + \beta V^2}{\alpha + \beta v^2}\right) = \frac{s}{r} . \qquad (11\text{-}2\text{-}7$$

In equation (11-2-7), α and β have been replaced by $\frac{2}{3}\alpha$ and $\frac{2}{3}\beta$, respectively, in accordance with Didion's experimental evidence for elongated projectiles. Using the values given above, it was found that $\beta \sim 50$, which is certainly very reasonable. The density ρ might of course have been nearer 8 g cm^{-3}, as Urey (1952c) believes, but it should be noticed that a measured length s has been inserted in equation (11-2-7) whereas, in actual fact, there would have been spaces where resistive forces were considerably smaller than those assumed in the derivation of the formula, and hence s should have been reduced by an unknown factor. The value of ρ can be considered to incorporate this factor.

It was shown by Didion that equation (11-2-2) held for velocities ranging from 0·09 to 0·54 km sec^{-1}. The analysis which has been pursued above incorporated velocities as large as 1·68 km sec^{-1}: at such velocities, there might be reason to doubt that equation (11-2-2) would hold equally well, but, nevertheless, it is reasonable to suppose that it would, at least, provide a first order result, and the value of β which has emerged from the analysis is of the order of the value

required to satisfy the conditions which very probably apply to the lunar rocks.

So far, only the valleys in the Ptolemaeus regions have been considered. Whilst these valleys are roughly parallel to one another, many authors have preferred to class them in a family of topographical markings each component of which runs into Mare Imbrium. The geologist G. K. Gilbert (1893) produced a chart (Fig. 11-2-2) of this "radial" system after only a limited amount of

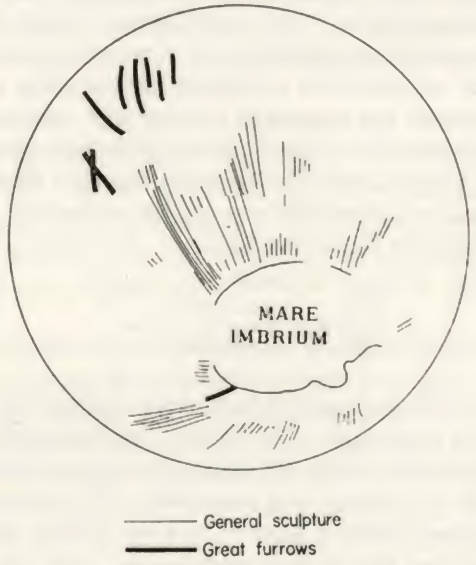


FIG. 11-2-2. Chart of system radial to Mare Imbrium: Gilbert (1893)

observational work at Washington. Darney (1933) has added many more radial markings to his chart, reproduced in Fig. 11-2-3, and Baldwin (1942) has based his chart (reproduced in Fig. 11-2-4) upon photographic observations. Reference should also be made to Figs. 11-3-4, 11-3-5, and 11-3-6. The fact that so many authors have discussed this Mare Imbrium system is proof that the radial markings are sufficiently prominent to attract the attention of even the casual observer.

As can be seen from any of these charts, a body ejected from Mare Imbrium to produce at circular velocity a valley in, say, the Hind region, could not do so without intersecting the eastern end of the

FIG. 11-2-3. Chart of system radial to Mare Imbrium: Darney (1933)
(Bull. Soc. Astron. de France)

Apennines. Now if any resistive effects were experienced in passing through the Apennine peaks, the original velocity of projection must have been greater than V, being reduced to the value of $1{\cdot}68\ \text{km sec}^{-1}$, or thereabouts, thereafter. The value $\beta = 50$ can be used to investigate this and, for an Apennine groove of 30 km length, such as is to be found about 160 km north-west of Eratosthenes' centre, it is found that velocities of at least $4V$ would be required. This process therefore seems to be rather improbable. Consequently, the projectiles that formed the grooves in the Hind region must have approached the local horizontal at angles of a few degrees, the velocities being elliptical but very nearly circular. Such projectiles might have ricocheted.* One would expect that ricocheting would occur for targets of small tensile strengths, but not for targets of large tensile strengths.

Splash bodies of parabolic velocity would fail to clear the Apennines when glancing projections commenced within 130 km of these mountains. For glancing projections closer even than 100 km, bodies of very large velocity would intersect the mountains but would have greater thicknesses to pass through. Had glancing projections occurred further away from the Apennines, the mountain chain would not have been scored except by bodies having elliptical velocities, the *near* foci of the ellipses being at the centre of the Moon. This allows a probable maximum diameter of 570 km to be set to a "ghost" crater which, as Urey (1952c) has pointed out, is located eccentrically in Mare Imbrium. Baldwin (1949a) gave its diameter as greater than 300 miles (483 km). The diameter which has been deduced here is in agreement with that which can be observed by virtue of the remaining, unmelted ringwall fragments.

Dynamically, then, assuming that substantial fracturing of the missiles would not ensue soon after first contact—and this assumption has not been proved—it would seem as if the process envisaged was wholly plausible. (Firsoff (1959a) objects to this idea on the grounds that the focus of an explosion would be underground and that it would therefore be impossible for bodies to be projected horizontally at circular velocity. This reasoning is unsound because the process might not have been explosive and the "focus" might easily have been above ground level.)

* The author is indebted to Dr. R. B. Baldwin who supplied a description of experiments with rifle bullets on the sandy shores of Lake Michigan.

FIG. 11-2-4. Chart of system radial to Mare Imbrium: Baldwin (1942). (*Popular Astronomy*)

The Alpine Valley is an interesting feature which should be considered. Viewed under small magnification the Valley does appear to be a perfect cut—cigar shaped, rather than of constant breadth—through the Alps. Its orientation is such that it fits in perfectly with the rest of the radial valley system: Fig. 11-2-4 shows

this well. If some different origin were proved for this particular Valley the whole process of valley-formation by the action of projectiles would, in the author's opinion, be thrown into doubt. The detailed differences between this and other valleys of the system can, however, be explained if it be assumed that the fragment which produced the Alpine Valley moved nearer to the roots than to the peaks of the mountains, and with a great deal of momentum. The ratio s/r must be increased by a factor of at least three. This presents no difficulties, since this factor can be absorbed by suitable adjustments to ρ and V. If, for instance, it is supposed that the fragment was composed of nickel–iron of $\rho = 8$, an initial velocity of nearly 2 km sec^{-1} would be required.

On this assumption, the projectile must have plunged deeper than those considered above, and friction acting along the shear surfaces would contribute energy to vaporize parts and melt other parts of the floor of the Valley. However, the time of heat generation would be so short that this source of heat would be insufficient by itself to explain the levelling of the floor of the Valley.

Kuiper (1954a) prefers to explain this feature as having originated when the mountains separated under tension and magma welled up to fill the resulting gap. Again, it has been argued by Moore (1952b) that the Alpine Valley cannot have come about as the result of a grazing collision since there are parallel and transverse valleys. The existence of these features has been confirmed by the author (see 11-3), and it is obvious that the Imbrian collisional hypothesis can not account for all of these linear markings simply by the grooving actions of projectiles.

For these reasons, it seems to the author that Firsoff's (1956e) suggestion that the elongated blocks lying coaxially in some of the valleys are simply portions of the walls of the valleys which have broken loose and tumbled over, should be considered very seriously. Firsoff's (1956c) criticisms that there is not a radial system are, on the other hand, not acceptable, for the appropriate radialism to the south-east, south-west, and the north-west of Mare Imbrium is unquestionable (see Fig. 11-2-4). Not only are there valleys forming this system: one of Gilbert's (1893b) conclusions was that "a collision of exceptional importance occurred in Mare Imbrium and one of its results was the violent dispersion in all directions of a deluge of material—solid, pasty, and liquid". The "pasty" phase certainly

seems to exist. Baldwin (1943) has noted that the well-known radial ridges, the distorted craters and, finally, the grooves or valleys, all form a convincing proof of the central explosion hypothesis. These features, he noted, are to be found in the above order at increasing distances from Mare Imbrium. The question of the so-called "pasty" phase will be discussed in 11-3.

It is logical to ask if other lunar seas have their own radial families. It seems certain that the seas which have roughly circular boundaries suffered similar origins. If therefore, Mare Imbrium had been produced by a collision of some sort, one might expect to find similar relationships between each sea and the sculpturing of its surrounds.

Urey (1957d) has suggested that *low velocity* impacts were responsible for the formation of maria and that no radial pattern is exhibited by Mare Serenitatis because the impact was directed normally to the surface, whereas an oblique impact in Mare Imbrium splayed materials in preferred directions—mainly to the south side of the Sea. The asymmetry of the radial pattern is not entirely proven, since Mare Imbrium is centred near to the north pole, but, if we make the assumption that the pattern is asymmetric, then the concept of any type of impact mechanism other than that incurring very small velocities must be ruled out. This would mean that the colliding body must have been of planetoidal rather than of meteoritic dimensions. With such large bodies, the author finds it difficult to envisage even a normal collision with no appreciable radial dispersion of matter. There are many large craters which display symmetrical radial markings and consequently some suspicion must be attached to Urey's suggestion that these craters, too, were produced by small-velocity objects colliding with the Moon.

The absence of radial markings around Mare Serenitatis is duplicated in the continents around other seas. Mare Humorum shows distinct radial ridges near to Capuanus (see Fig. 11-2-5); Mare Crisium may be associated with radial markings near the northern shores; but more careful examinations reveal that, in each case, these localized ridges and valleys are specially placed components of a more general family of parallel striations. Clearly, some components of any family of parallel lines which intersect a circle will run along radii of the circle, and it would seem that the two cases cited would be examples of this situation.

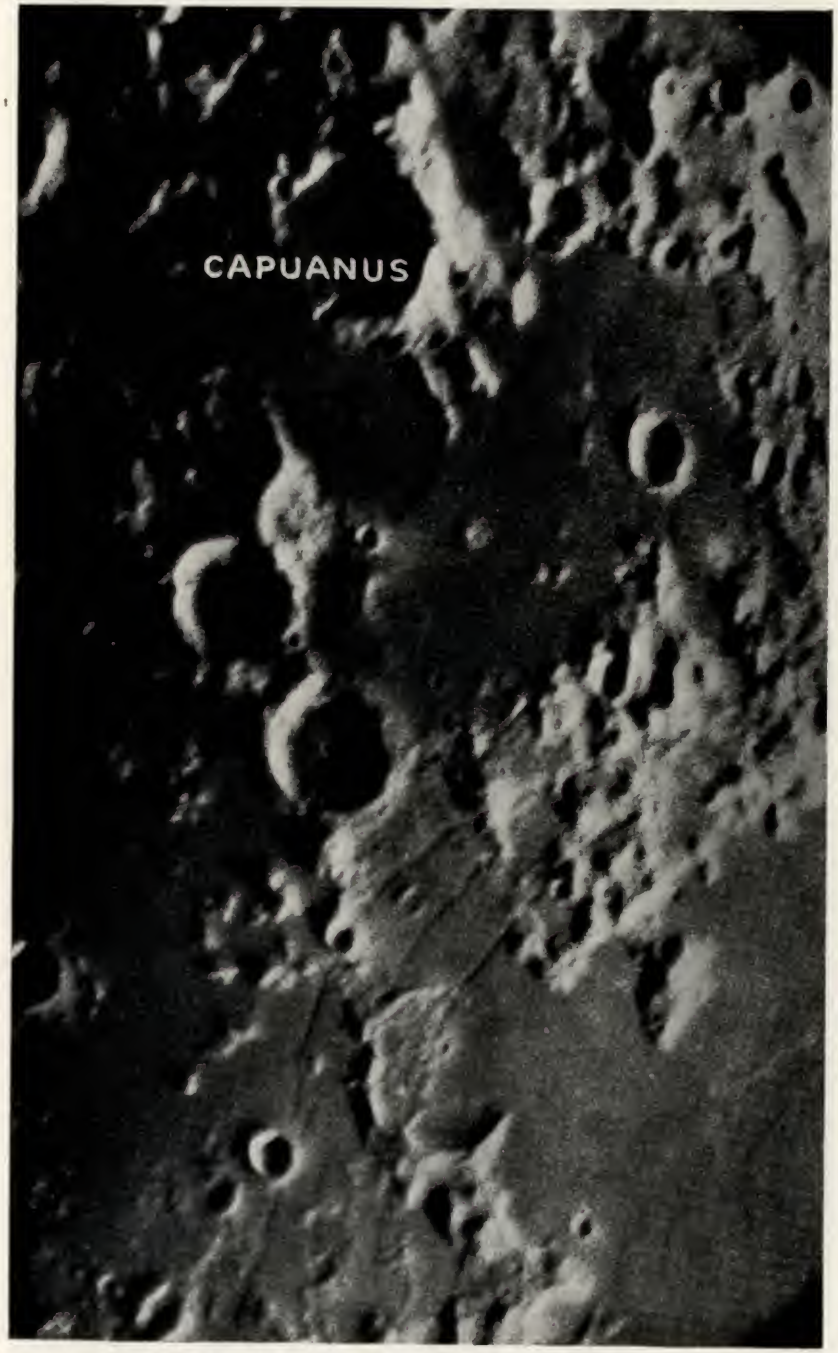


FIG. 11-2-5. Aligned ridges near to Capuanus

FIG. 11-2-6. Crater chains south of Mare Nectaris

The Rheita Valley (Fig. 11-1-3) points into Mare Nectaris, and there are other crater chains—particularly to the south of Mare Nectaris, such as those shown in Fig. 11-2-6—which run roughly radially to this Sea. Moore (1956d) pointed out that some of the valleys in the Ptolemaeus regions were in fact crater chains. Components of these chains are rarely perfectly formed craters: often their walls of contact are absent and the chain resembles a narrow groove or broad valley with crateriform walls. It is sometimes difficult to distinguish walls which might be indented merely due to accidental causes, and true crater-cupped walls. In any event, the crater chains do exist and have not been satisfactorily explained by the impact adherents. It seems to the author that their origin must be igneous. (A discussion of the origin of some crater chains will be found in 12-4.)

One other difficulty associated with the supposed collisional process is that the trending in the Jura Mountains is predominantly parallel to the shores of Mare Imbrium. Here, there is a marked absence of all but a few radial forms, and two of these are short crater chains. It is still possible, however, that the parallel ridges here may have been the results of the actions of surface waves.

11-3. **Intersecting grids**

Craters of diameters in excess of 20 km have, in general, polygonal rather than circular boundaries. Puiseux (1908) is one of the many authors who has discussed this problem, and the map of Lamech (1946) shows a great number of polygonally-shaped craters. Whether by chance or not, in many cases one or more of the straight parts of the ramparts of a crater, if produced in the same straight line, would lie along some other linear feature, such as a ridge or crater chain.

Graff (1929) found evidence that the Moon had possessed plastic properties up to a time after the formation of the larger craters. "Lateral forces (either compressions or tensions)" he wrote "perhaps arising during cooling, might very well have altered the geometrical shapes of craters, so that the observed polygonal forms might thus be explained". Alter (1956a) has described many polygonal craters, and crater chains leading from the walls of these craters. Matoušek (1924a; 1924b) noticed that the borders of Sinus Iridum did not form the arc of a circle, and that the surrounding mountains were cut up by "fracture systems". Promontories Laplace and Heraclides

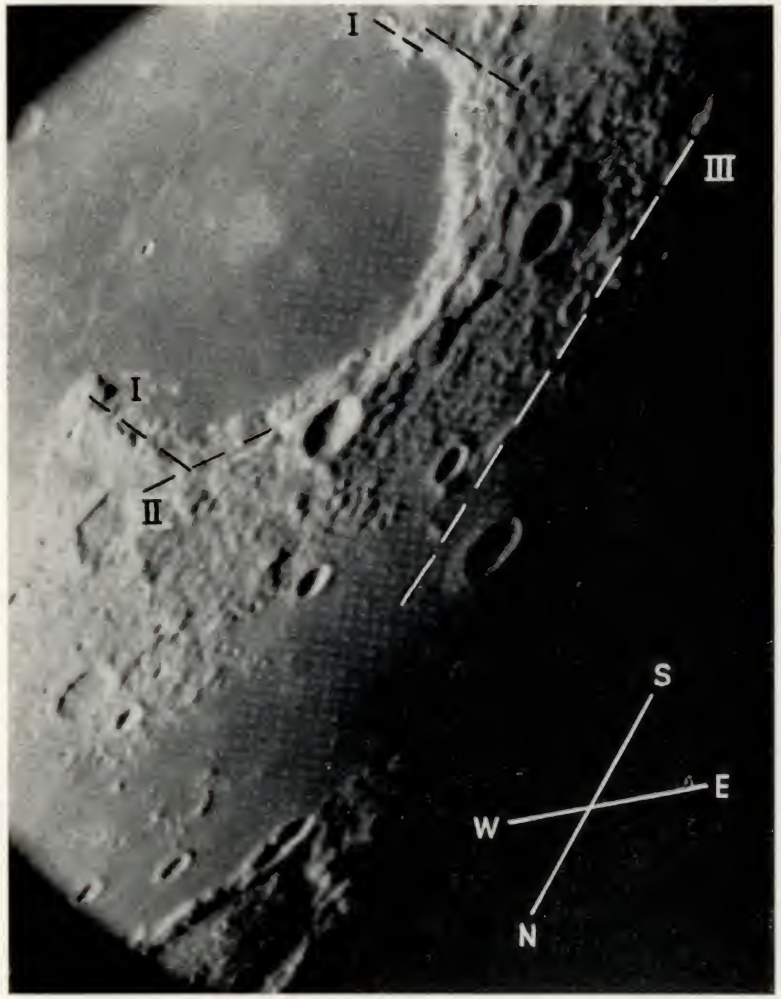


FIG. 11-3-1. Trending in the mountains bordering Sinus Iridum

were bordered by parallel fractures up to their extreme tips. Matoušek recognised three main fracture systems in this vicinity: (see Fig. 11-3-1) system I, running WSW. to ENE., the oldest; system II, cutting ESE.–WNW. across the first system, and hence younger than system I; and system III, containing the most recent dislocations, running N–S. A suggested cross-section of the region was included

in Matoušek's (1924b) paper and this indicated an igneous origin for Bianchini and the craters in the Bay, and showed possible faulting planes.

Appropriate to this discussion is the following passage from *L'Annulaire pour 1956*: "The mountainous regions have . . . prominent dykes, rectilinear . . . and disposed in parallel groups. Several of these dykes lie along common tangents to the walls of many craters. They appear to have limited the development of the latter, imposing on them polygonal forms.

"A detailed examination of the lunar relief indicates that the tendency has been for tensions in the crust to predominate over foldings".

It is the opinion of the author that this last suggestion would be very difficult to prove. Rilles have for too long been thought of as cracks: certain difficulties in such suppositions are set out in Chapter 12, and the author (1957a) has shown that the ratio of the frequency of folding to that of normal-faulting in the Moon would, in all probability, have been greater than the corresponding terrestrial ratio. Such a conclusion might not hold if, for instance, large impacts had caused appreciable fracturing, but the observational difficulties would still remain.

That polygonally-shaped craters are common cannot be doubted. Were the larger craters formed, like the smaller craters ($\lesssim$20 km in diameter), with circular boundaries, later to be distorted into polygonally-bounded depressions, or have they had polygonal boundaries from the beginning? One would have expected meteoritic collisions to have produced circular craters, yet, as Zimmerman (1948b) and others have pointed out, the Arizona crater—presumably of meteoritic origin—is markedly polygonal. Furthermore, Prinz (1893a) found that Mauna Loa, Kilauea, and other terrestrial basalt-lava-volcanoes, had polygonal forms, It would therefore not be sound to argue from this point of view that the smaller and larger lunar craters were not of similar genesis. In fact, there is some evidence that the craters were distorted by crustal movements, after they had been formed.

Let us return to consider in more detail the "pasty-phase" of Gilbert's (1893b) Mare Imbrium pattern. When examined even very carefully under good conditions, the apparently smooth, radiating ridges might look, as Gilbert remarked, like splash marks. It is not

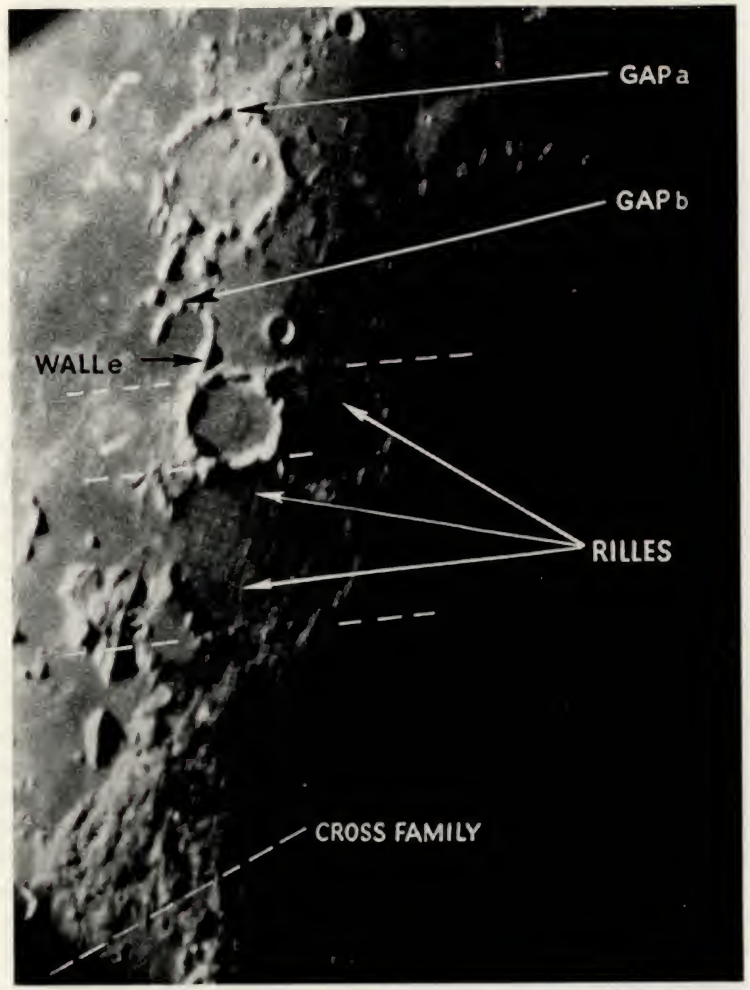


FIG. 11-3-2. The Fra Mauro region: evidence against the hypothesis that matter was ejected from Mare Imbrium

until one has just the right conditions that one notices that these ridges *always form parts of the walls of some much-eroded crater*.* Hence, they cannot be splash-marks. Furthermore, if we suppose that the walls of such craters were carved up by projectile action, we encounter serious difficulties. For example, Fig. 11-3-2 shows the

* Moore (1957b) has come to the same conclusion, independently.

Fra Mauro region. It seems scarcely likely, physically, that the walls at *a* and at *b* were hinged back, to form the bottleneck-gaps which we see, by the action of flying bodies. The walls of the craters do not show evidence of having been pushed southwards at all: on the contrary, the walls are sometimes elongated in a northward direction (see wall *e*) to an extent which certainly can not be explained by the process under consideration. Such phenomena suggest a less superficial origin for these ridges.

Of the valleys, Tomkins (1907) has said, ". . . they seem to be due to faulting or folding . . . they appear to indicate lateral pressure. Those in the neighbourhood of the Alps may perhaps throw some light on the origin of the Alpine Valley; is it possible that we have there a case of faulting?" A picture of the Alps is reproduced in Fig. 11-1-2. After most careful and extended telescopic observation, the author, confirming an earlier suggestion of Moore's (1952b), has concluded that the reason why the Alps and the Caucasus are so different from other mountainous regions is that they are cut up by two intersecting families. The Alpine Valley belongs to one family of linear markings, and the direction of the other family is indicated in Fig. 11-3-7.

Turning now to the Rheita Valley, Loewy and Puiseux have said "Its edges are parallel and widely separated, cutting through several old craters, and are, contrariwise, interrupted by many recent volcanoes. The existence of oblique ridges across the valley excludes the idea of a superficial origin, and indicates a basal cause". Sadil (1953) has said that the Rheita Valley is "a great, tectonic fault passing through a series of consecutive craters. The length of this valley is approximately 200 km; and if we associate with it a further, less distinct, continuation in a south-westerly direction, the actual length of this fault—which has no analogy on the Earth—would be about 450 km".

The observed ellipticity of the craters in the wider stretch of the Valley is greater than would be predicted from the effect of the surface curvature. This is due to the fact that the contact walls of this chain of craters have been distorted in the north–south direction. Observing from the Pic-du-Midi, the author found that these distortions were continued in prominent ridges for vast distances to the south side of the Valley, and one or two parallel markings were found on the other side. The direction of this family is shown in Fig. 11-1-3.

That the main axes of the Valley lie parallel to faults is probable. There exist several very definite faults on the Moon. The Burg fault, the fault crossing the Alpine Valley, and even the one in the east of Mare Humorum, seem to be members of one family. This family intersects the Alps and Caucasus, and continues round to Mare Crisium, up the west limb regions and across the central highlands to the shores of Mare Humorum. In this family one may possibly include the Straight Wall (Fig. 11-3-3). Rilles, when straight, often seem to lie in a family, as is shown in Fig. 11-3-2.

All these phenomena must be closely related: charts of the grid system drawn by Habakov (1949c), von Bülow (1958), and Firsoff (1959a), have been reproduced in Figs. 11-3-4, 11-3-5, and 11-3-6, respectively, and the author's preliminary chart of the grid system has been plotted in Fig. 11-3-7. All these charts were apparently drawn quite independently,* and it is most gratifying to note that there is a substantial amount of agreement between the different observers. The agreement between von Bülow's chart and the author's is particularly striking. The radialism around south Mare Imbrium shows prominently, and it is obviously connected with the formation of Mare Imbrium itself. A large impact could produce large stresses and initiate faulting even at great distances from the origin. Kuiper (1959b) has pointed out that the Sirsalis Rille, about 500 km long, is radial to Mare Imbrium and is almost diametrically opposite to the Alpine Valley. The N. Rheita Valley is roughly orthogonal to these features. If we assume that the craters were initially circular, and observe the heights of faults, we may say that the observed crustal displacements in both horizontal and vertical directions have been only small fractions of the diameters of the large craters.

Since the valley-system of the regions in the centre of the disk and the striae of the Haemus Mountains are roughly parallel, in conical projection, to the families which border Maria Crisium and Humorum, it seems as if they might all be associated. Again, there are ridges which intersect the most prominent central striations nearly orthogonally, and these are parallel to the ridges crossing the Rheita Valley, and the ridges in the south and north polar regions. This family is very distinct in the Jura Mountains and delicate components can be traced all around the inside walls of Sinus Iridum. An excellent

* I am indebted to Dr. P. Hédervári who, in 1960, kindly drew my attention to the charts of Habakov (or read Chabakow) and von Bülow.—*Author.*

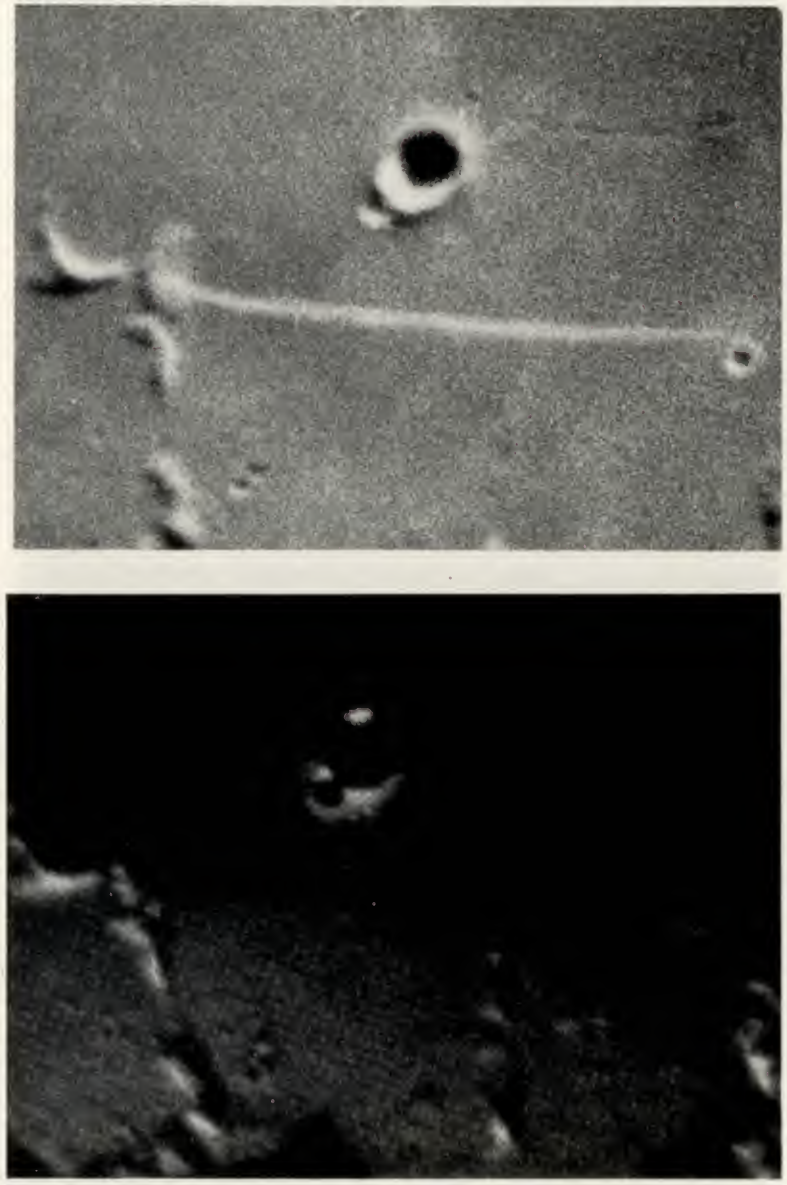


FIG. 11-3-3. The Straight Wall: a lunar fault as it appears at (a) sunrise, and (b) sunset *(right)*

description of the grid system has been given by von Bülow (1957f). He believes Mare Imbrium to be a collapse feature which has become filled with lava: he considers this view to be more practicable than one involving a catastrophic origin.

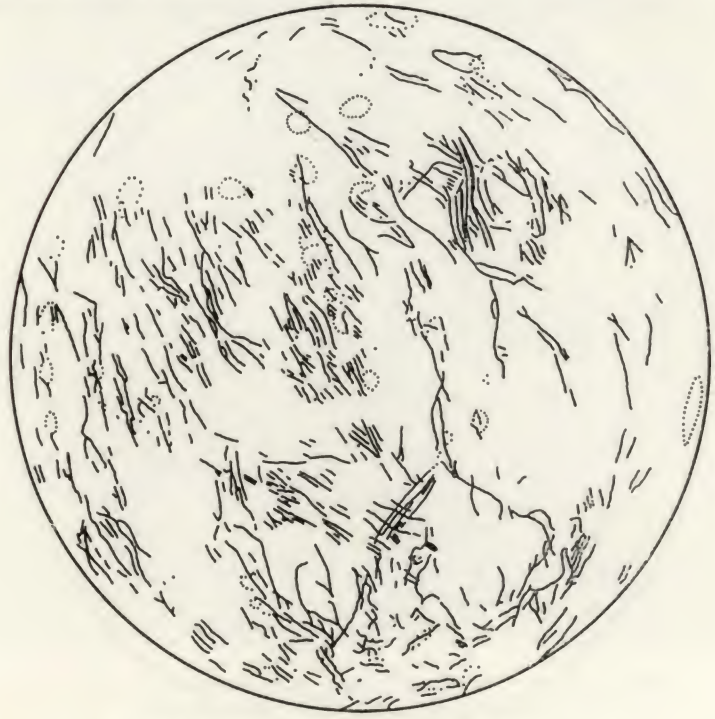


FIG. 11-3-4. Chart of the grid system: Habakov (1949)

Thus, it is suggested that parallel families represent a more general phenomenon than do radial families. Anderson (1951) has stated that linear parallelism of faults and dykes indicates *directional* uniformity of stress, and that, if such features extend over large distances, *quantity* uniformity of stress is indicated. Since the weight of rocks generally interferes with the uniformity of crustal stresses, there would be more chance of finding the results of uniform stresses near to the Moon's surface than there would be near to the Earth's. These facts suggest that the stresses which formed the lunar grid-system were fairly constant both in amount and direction.

It is not at this stage easy to come to any conclusions as to the origin of the grid-system, but assumptions that the release of crustal stresses has played a major role in its development have led the author (1960a) to explain certain of its features. Two forces which approach the requirements most closely are those which may be

FIG. 11-3-5. Chart of the grid system: von Bülow (1958)
(aus v. Bülow, 1958/59)

attributed to the non-equilibrium form of the Moon, and the forces due to the Earth's attraction. Both may have differed in magnitude appreciably, in the past. The forces arising within the Moon due to a change in the eccentricity of the central meridian would surely have been very uniform over long periods of time. Urey (1957c; 1960b) has noted that such a change would result most naturally in tensions in limb regions and compressions in the centre of the disk. The grid is well developed in polar regions, and the author has verified the approximate charts of Spurr (1948a). Such patterns could not have resulted from tensions in the surface alone. Again,

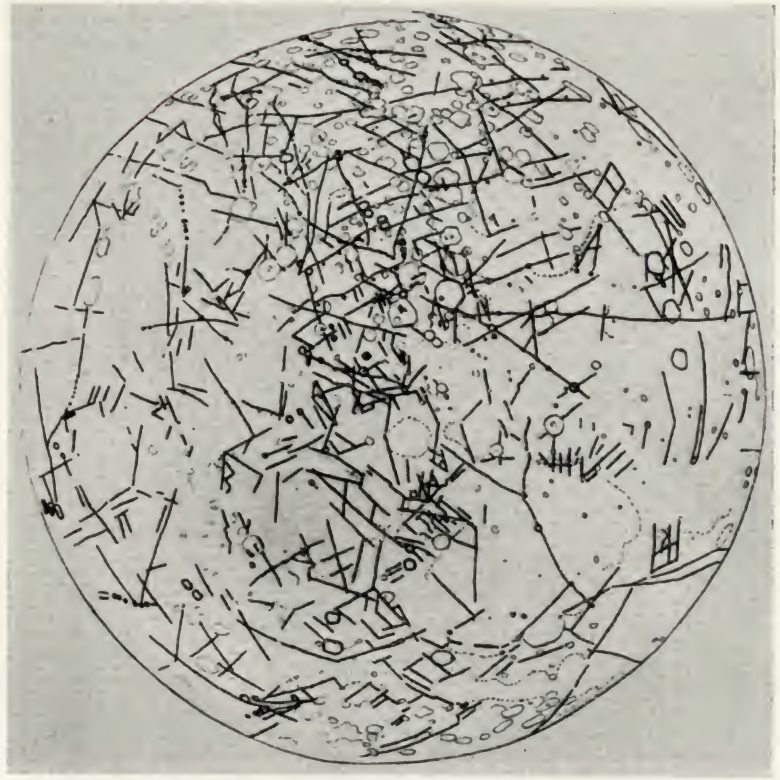


FIG. 11-3-6. Chart of the grid system: Firsoff (1957). Revised (1959).
(*Strange World of the Moon*, Hutchinson.)

the existence of the Ariadaeus, Hyginus, and Triesnecker rilles in the centre of the disk do not suggest—at least on casual examination—that there have been no tensions there. However, the problem may be one of relative pressures rather than one involving absolute tensions. Alternatively, an expansion, followed by a compression, of the surface might explain the facts. The expansive phase might not be necessary: in a private discussion, Urey (1957d) suggested to the author that cracks might have originated during large collisional processes.

The time of origin of the grid system may be estimated, in principle, from a knowledge of the rate of formation of craters which are

FIG. 11-3-7. Chart of the grid system: Fielder (1957). Revised (1960)

superimposed on the grid markings. Such craters all seem to be less than 20 km in diameter.

Watson (1956b) and Baldwin (1949a) have together listed a total number of terrestrial meteoritic craters of 15. Of these, perhaps 5 would have had diameters of the order of 1 km in the absence of an atmosphere. Öpik (1950) has estimated that the total area of the Earth's surface which has been searched for such craters is 3×10^6 km^2, and he maintains that craters older than $0{\cdot}5 \times 10^6$ years would not be detectable on the Earth's surface, because of erosion. Using these data, there must have been at least 10 craters of diameter 1·0 km formed by meteoritic impacts with the visible surface of the Moon in the last 10^6 years. The law which relates the numbers and masses of interplanetary bodies is, however, not known,

and so it is not possible to say how often a crater 20 km in diameter would have been formed on the Moon, even at the present rate of bombardment.

This problem of the lunar grid system is of the greatest importance. In the past, it has received too little attention from observationalists and practically no attention from theorists.

11-4. Lattice patterns and their time of origin

It has been shown above (11-3) that the grid systems which Spurr (1948a) described are actually parts of a more general grid system which consists, in any element of surface, of linear ridges or mountain chains, valleys, faults, or crater-chains. Spurr (1949b) also introduced the term "lattice pattern" to describe the intersecting ridge systems which occurred, he observed, to the north and south sides of certain craters. Among these, he listed Eratosthenes, Cyrillus, Rhaeticus, Sacrobosco, Pontanus, Gemma Frisius, Copernicus, Timocharis, Reinhold, Posidonius, and Aristoteles. The author has concluded that these lattice patterns occur even more frequently than one would be led to believe by reading Spurr's works, and, furthermore, that the patterns always form local portions of the general grid system.

The fact that the lattice patterns do appear to the north and/or the south aspects of craters (and not on their eastern or western sides) suggests that the term "lattice patterns" has been attributed to phenomena of special significance and, hence, that the term should be retained in the literature, in spite of the fact that the individual patterns form parts of the grid system.

A Pic-du-Midi picture of Arzachel and its surrounds has been printed in Fig. 11-4-1. The lattice pattern immediately south of Arzachel is plainly shown, even though the details have been lost, in the photograph. In Fig. 11-4-2, the pattern has been inked in. It will be noticed that it is intimately connected with the lines which mark the polygonal boundaries of craters in the vicinity.

Several other lattice patterns, which Spurr has not mentioned, have been observed visually. In general, the lattice disturbances cut into the north and/or the south ringwall of a crater, and, when this situation arises, the walls of the crater appear to be lowest at these places. (In this context, the word "appear" is important, because the observer must be wary of conclusions which have necessarily been influenced by the restricted orientation of the plane in which the Sun rises.)

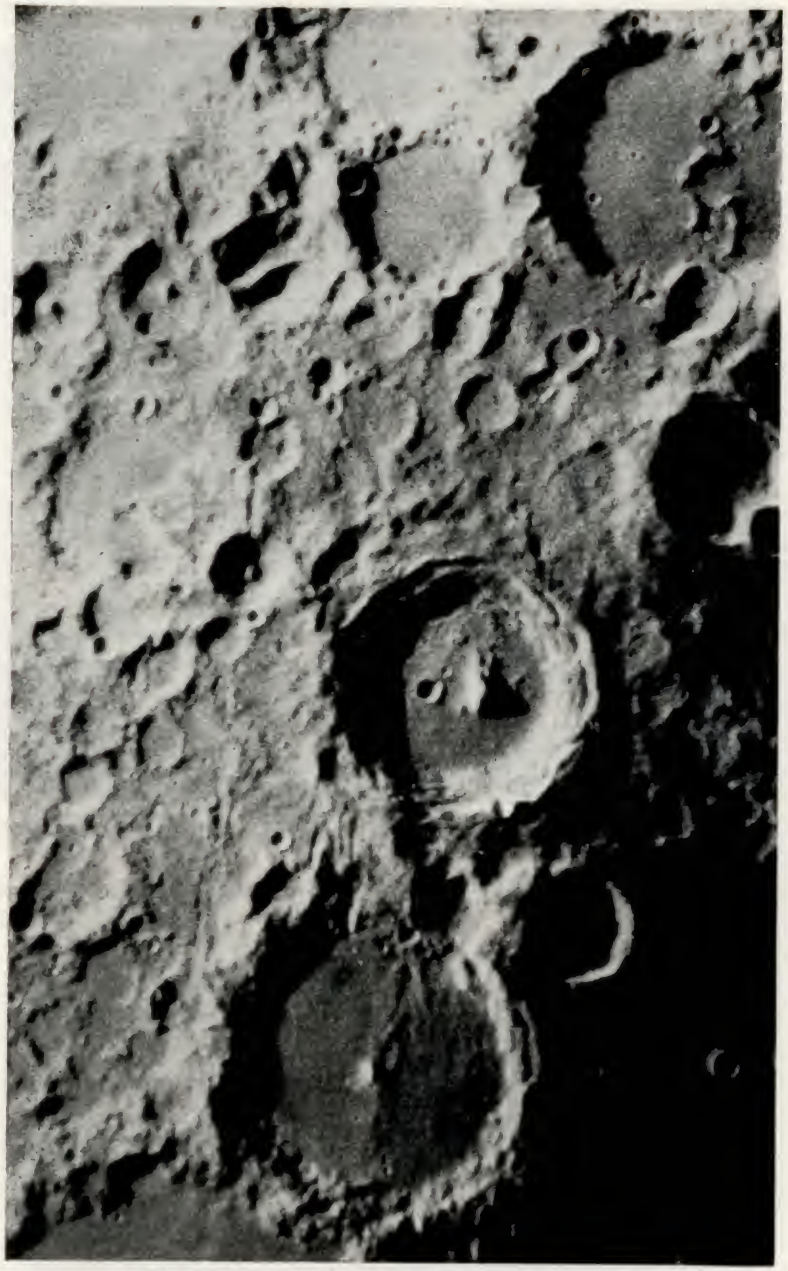


FIG. 11-4-1. Arzachel and its immediate surrounds

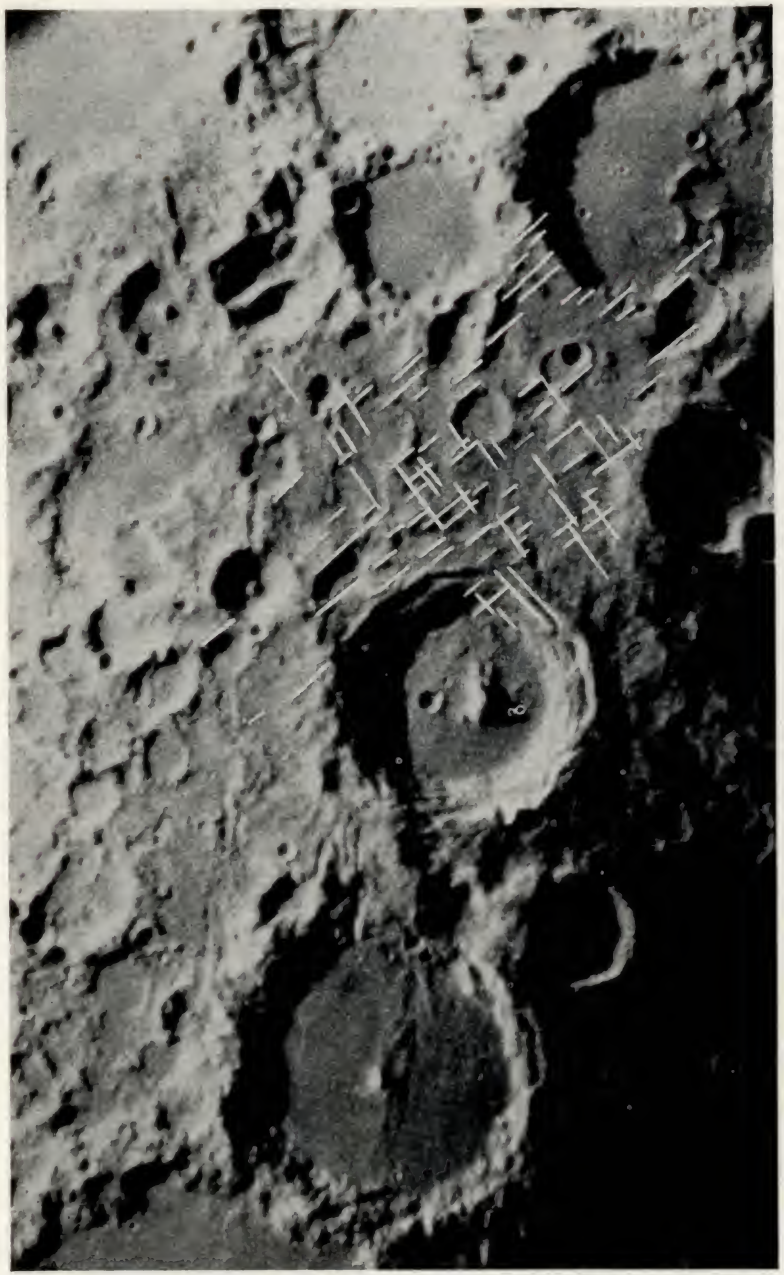


FIG. 11-4-2. The lattice pattern immediately south of Arzachel (cf. FIG. 11-4-1)

N

Tycho, often quoted as being one of the youngest craters on the Moon, has suffered such modification: narrow ridges, visible only under the best of conditions, pass down the *inside* walls. The boundary of Tycho has been distorted into a polygonal shape and the local lattice pattern is well developed and can just be detected on *both* north and south sides of the crater in a photograph by Alter (1957e),* taken with the 60-in. reflector at Mount Palomar.

A visual study of the lattice patterns has indicated with no uncertainty that some components were formed *after* craters of the order of the size of Tycho. There must therefore have been mountain-forming activity on the Moon more recently than the formation of Tycho.

However, a suggestion that this activity was allied to the formation of the larger craters themselves arises when it is considered that the lines of the lattice-patterns are often parallel to the linear portions of crater walls.

A consequence of these results is the further suggestion that the grid-forming activity was attenuated in time, and that, during the active interval, large craters assumed their final shapes. A quiescent period or periods may have occurred within this active interval (the present argument does not exclude this possibility) in which case there may have been two or more periods of grid-forming activity. No proof that such was probably the case has been established here.

A probable sequence of events in lunar history may be stated as follows:

Craters of diameters $\gtrsim$ 20 km → Grid structures and lattice patterns → Craters of diameters $\lesssim$ 20 km

The first and second, or the second and third, periods may have overlapped. Two major problems are to estimate the times for which these changes operated, and the "absolute" time scale, but the present problem is merely to establish as well as possible the sequence of events. The sequence may be studied by the use of first class photographs supplemented by visual observations under good conditions. Photographs of the Moon taken from Earth-satellites might eventually be valuable.

* The views expressed by Alter in the paper which accompanies his excellent photographs are supported by the author.

It seems odd that neither the grid system nor the lattice patterns have received much attention in the past. Thorough study of general phenomena such as these would be very valuable in connection with the study of the origin of the Moon's surface.

11-5. Summary

Linear-type features, comprising valleys, rilles, faults, and ridges are associated in a network or "grid" of intersecting families, the members of each family being roughly parallel to one another. There is a very clearly marked "wheeling movement" of the grid markings around a centre located in Mare Imbrium and, although it is wholly possible that a large scale collision in this region contributed substantially to the formation of this radial fan, there is clear evidence that such a collision could not account for certain members of the fan.

Fan-like markings do not seem to be associated with other maria and, in general, the grid system seems to have its origin in major stresses which at one time were imprisoned in the crust of the Moon.

Lattice-patterns (associations between craters and the grid system) and the system radial to Mare Imbrium, suggest that crater-forming activity may have relieved crustal stresses.

It is important to study the relative times of formation of all the surface features of the Moon by considering them in conjunction with the markings of the grid system.

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CHAPTER 12

Rilles, Faults, and Wrinkle Ridges

12-1. Description and distribution of rilles

A rille is a snaking depression in the Moon's surface; in form, it is rather like the dried-up rill of the Earth's surface. The various names *rillen* (German), *rainures* (French) and *clefts*, *cracks*, *rills* or *rilles* (English) are commonly used as if they are synonymous. According to the Oxford Dictionary, the correct word is *rille* and this word will be used throughout this book. It will be shown (12-2) that there is no basic difference between features such as the large Ariadaeus "Cleft" and a host of narrower, crack-like features: all of these features will, therefore, be referred to as rilles. According to Schmidt (1866), these "trenchlike channels or valley-forms" were first studied by Schroeter, and were named by him "Rillen" (English: groove; channel). In the past, there has been a general misunderstanding about the nature of the rilles. Arago (1858) said ". . . they may be divided into two classes—the flat and broad type . . . and the narrow ones of greater depth and often with steep sides with serrated edges". This is simply not correct, yet even recent texts repeat the old descriptions. Baldwin (1949) has written, "Near Triesnecker is a group of short irregular *cracks*, very jagged in appearance, which seem to be *bottomless*" (author's italics). On the contrary, visual examination of this system of rilles, from the Pic-du-Midi, has satisfied the author that the wider branches, at least, are quite shallow, with apparently smooth edges. In fact, all similar features which were of sufficient width for the purposes of detailed examination appeared to have depths which were much smaller than their respective widths.*

* The author wishes to thank Lenham and Whitaker (1955a) for having suggested this fact, as a fruitful result has been obtained from the simplest of observing programmes.

Having established this much, it was soon further established that the bottoms of many of the widest rilles, rather than being flat or concave, were humped up, longitudinally (see 12-2).

The above description applies to what may be called *normal* rilles. Another type of rille is the *crater* rille (12-2) which has probably evolved largely along essentially similar lines to those of the normal rille (see 12-4). Dollfus' (1956f) explanation of the crater rilles, namely, that they are normal rilles the borders of which have been chipped by the impacts of small meteorites, is believed to be incorrect.

An analysis of the data which Schmidt (1866) gave in his catalogue of rilles (425 rilles discovered by Schroeter, Schmidt, Lohrmann, Mädler, and Kinau) showed that 121 ran north–south, 107 ran north-east–south-west, 100 ran north-west–south-east and only twenty-one ran east–west. It is obvious that, because the sunlight is never directed from the north or south, the probability of detecting any linear depression or elevation of the same colour as its surrounds must in general decrease as the inclination of the linear feature to a meridian passing through it increases. Hence, there are, in all probability, many undetected rilles which run from east to west, and it is not justifiable to conclude that the majority of rilles run from north to south. On the other hand, only 17% of the rilles listed run in directions other than those mentioned above, and it is only possible to conclude that either the estimated directions may be wrong, in certain cases, by as much as 22°·5, or that the directions of the rilles are not distributed at random.

Two final characteristics of rilles must be noted. As Steavenson (1919) has pointed out, "when several occur in one region, they frequently exhibit a rough ... parallelism (e.g., Hippalus, Plinius, and Bonpland systems)". Secondly, it is often said that rilles are associated with particular craters. Certainly, rilles are often found curving within the walls of large craters and seas.

12-2. The detailed forms of rilles

The most conspicuous normal rille is that associated with the craters Ariadaeus and Silberschlag, and it is called the Ariadaeus Rille. It is near to the centre of the disk, is 5 km wide along its middle stretches, and is of the order of 270 km in length. Because of its great length it is very easily noticed by the observer with the smallest

FIG. 12-2-1. Ridges crossing the Ariadaeus Rille

of telescopes. Because its width is many times greater than the smallest distance which can be resolved with the naked eye, and a few times greater than the smallest distance which can be resolved by photographic means, it is easily possible to learn much about the detailed structure of this feature. Such a programme was carried out at the Pic-du-Midi by the author.

Prominent ridges crossing the Ariadaeus Rille have been labelled A, B, C, D, E, F and G, in Fig. 12-2-1. These ridges seem always to form parts of the distorted walls of old craters (see 12-4) and are members of the family which is so conspicuous in Fig. 12-2-1. In fact, the Rille is best described as a series of broad, shallow trenches,

the average depths of these being but fractions of their average widths. The stretches of the Rille which are reproduced in Fig. 12-2-2 were studied visually with the 60 cm, f/30 refractor around 21^h00^m U.T., 15 June 1956, with a magnification of 1026.

FIG. 12-2-2. A part of the Ariadaeus Rille: Gentili, Pic-du-Midi

Both edges appeared as bands of appreciable widths, and it was obvious that they were not by any means vertical: the slopes were coarse, and blocks of rock which must have tumbled down them could be seen lying along a belt defining the bottom of the north wall. Even smaller blocks were suspected at the bottom of the more brightly illuminated south wall. A most interesting thing was the fact that the shadow cast by ridge *B* over the bottom of the Rille was *concave*. The locus of all the tips of this shadow seemed to be part of the circumference of a circle. The shadow length cast by the same ridge as it passed over the land to the south of the Rille was much less than that cast inside the Rille. These observations indicated that the floor of the Rille was sunken with respect to the outside terrain and that, at this place, it was possibly convex upwards.

A search among the existing lunar plates at the Observatory yielded one which had been made by Gentili at 5^h11^m on 21 September 1951. Gentili had secured this negative by exposing for 5 sec on Agfa Rapid Red emulsion, with an auxiliary negative lens which gave the 60 cm refractor an equivalent focal length of 54 m.

JEREMIAH HORROCKS' OBSERVATORY,
MOOR PARK, PRESTON.

Figure 12-2-2 represents a small portion of this plate. When this picture was taken, the illumination was from the east—not from the west, as in the author's visual observation—but, nevertheless, ridge *E* was casting a shadow over the Rille bottom which was distinctly concave. Other ridges crossing the Rille gave indications of this phenomenon but none of these provided concrete evidence of it.

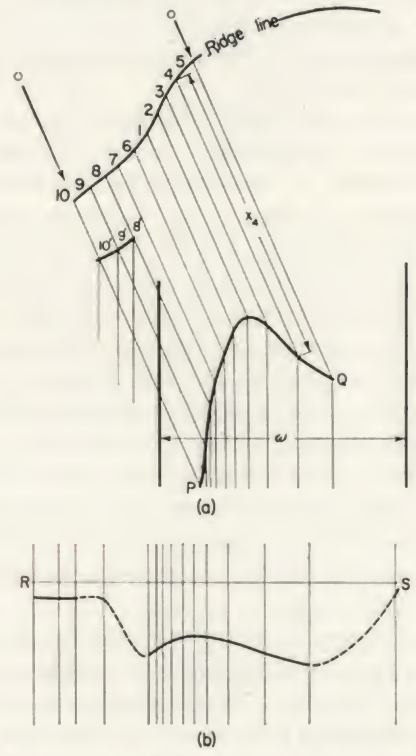

FIG. 12-2-3. The Ariadaeus Rille: (a) plan of ridge "*E*" shadow-boundary; (b) a profile of the Rille

Measurements $x_1, x_2 \ldots x_{10}$, of the shadow-lengths between the boundary of light and shade on ridge *E* (henceforth called the "ridge line") and the boundary of light and shade which joined the tips of the shadows cast by this ridge, were made with a microscope reading in microns (see Fig. 12-2-3a). An enlarged plan of the shadow edge—PQ in Fig. 12-2-3a—was constructed and points on

PQ were projected on a base line RS, as shown in Figs. 12-2-3a and 12-2-3b. The simple relationship

$$y_n = x_n \tan \alpha \qquad (12\text{-}2\text{-}1)$$

was then used to obtain the depth y_n of a shadow tip at position n, with respect to the point at the same position on the ridge line, where x_n is the corresponding plan shadow length and α is the elevation of the Sun. Three measurements, x', were made for positions 8, 9, and 10, on a short shadow cast by that part of the ridge which crossed the terrain to the south of the Rille.

The fact that the ridge line did not cut across the Rille at right angles—or even at a constant angle—and the fact that the projection of the sunlight was at 23° with the Rille-axis at the place under consideration, made no difference to the results: these things were allowed for in the geometry. It must be noted, however, that the profile shown in Fig. 12-2-3b is with respect to a ridge line RS which has been distorted in the vertical direction so as to take the form of a straight line. The distortions are thought to be small in comparison with the differences of level of the Rille-bottom. (But see below.)

It is seen from Fig. 12-2-3b, which is drawn roughly to scale, that the Rille is a sunken feature, having a convex bottom which is somewhat asymmetrical. The continuous lines cover those parts which were measured, whilst the dotted lines are only estimates from visual observations. The shadow of ridge *B*, noted at the telescope, certainly seemed to indicate the presence of a more symmetrical convexity just to the east of that ridge.

Another interpretation of the observed shadow forms might be to assume that the ridges had depressions at their crests, whilst the Rille-bottom was fairly flat. Wilkins and Moore (1955b) have said that Lohrmann traced the Rille through all the hills.

It is possible that Lohrmann noted the concave shadows and thus came to this conclusion, but Thornton pointed out to the author that one or two of the cross ridges in Gentili's photograph seemed to have cuts through them running parallel to and just inside the northern wall of the Rille, and probably it was these features which attracted Lohrmann's keen eye. In later visual work at the Pic-du-Midi the author was able to confirm that almost every cross ridge contained extremely shallow "nicks" at both the north and the south sides of the Rille, as shown in Fig. 12-2-5. The significance of these will be

mentioned in 12-4; the important question to ask here is whether or not the nicks might produce the observed shadow-forms even assuming that the bottom of the Rille was fairly flat. Without independent evidence that the bottom of the Rille was convex it would be difficult to find the correct answer to this question. However, the author has collected strong independent evidence that the Rille-bottom is of this humped form.

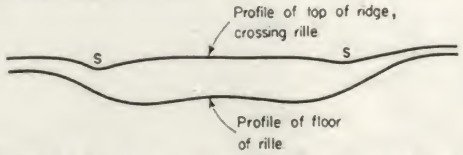

FIG. 12-2-5. Possible shapes, s, of " saddles " or " nicks " in a cross ridge

After the description given above had been circulated, it emerged that Whitaker (1956a) had made an earlier observation in which the Ariadaeus Rille had appeared to be split along its whole length. This phenomenon of interior shading is only just apparent on Gentili's photograph. Now, at certain altitudes of the Sun, a feature of the sectional form given in Fig. 12-2-3b, and with its axis inclined to the plane of the rising Sun, would reproduce the effect described by Whitaker. Hence, his observation not only confirms independently the author's results, but suggests that the whole length of the floor of the Rille is arched in this manner. Goodacre (1931) referring to that part of the Rille west of Silberschlag, wrote, "This . . . section has been seen by some observers to be double". Judging by Barker's (1954a) account, this doubling does not seem to be connected with the phenomenon with which we are now concerned. However, after having completed further visual work at the Pic-du-Midi, the author is now completely satisfied that the floor is convex along most of the length of the Rille. A careful drawing was made of the shadow forms inside the Rille, and the details were based upon an outline composed from a negative made shortly after the drawing was completed. The seeing was mostly very good, and the reader may compare the appropriate parts of the photograph (Fig. 12-2-1) with the drawing, which has been labelled and reproduced in Fig. 12-2-4. This figure is largely self explanatory, but a few points will be noted here.

(a) The ends of the main Rille are to be found in hilly country. In these locations the Rille narrows and becomes less deep and thus less conspicuous.

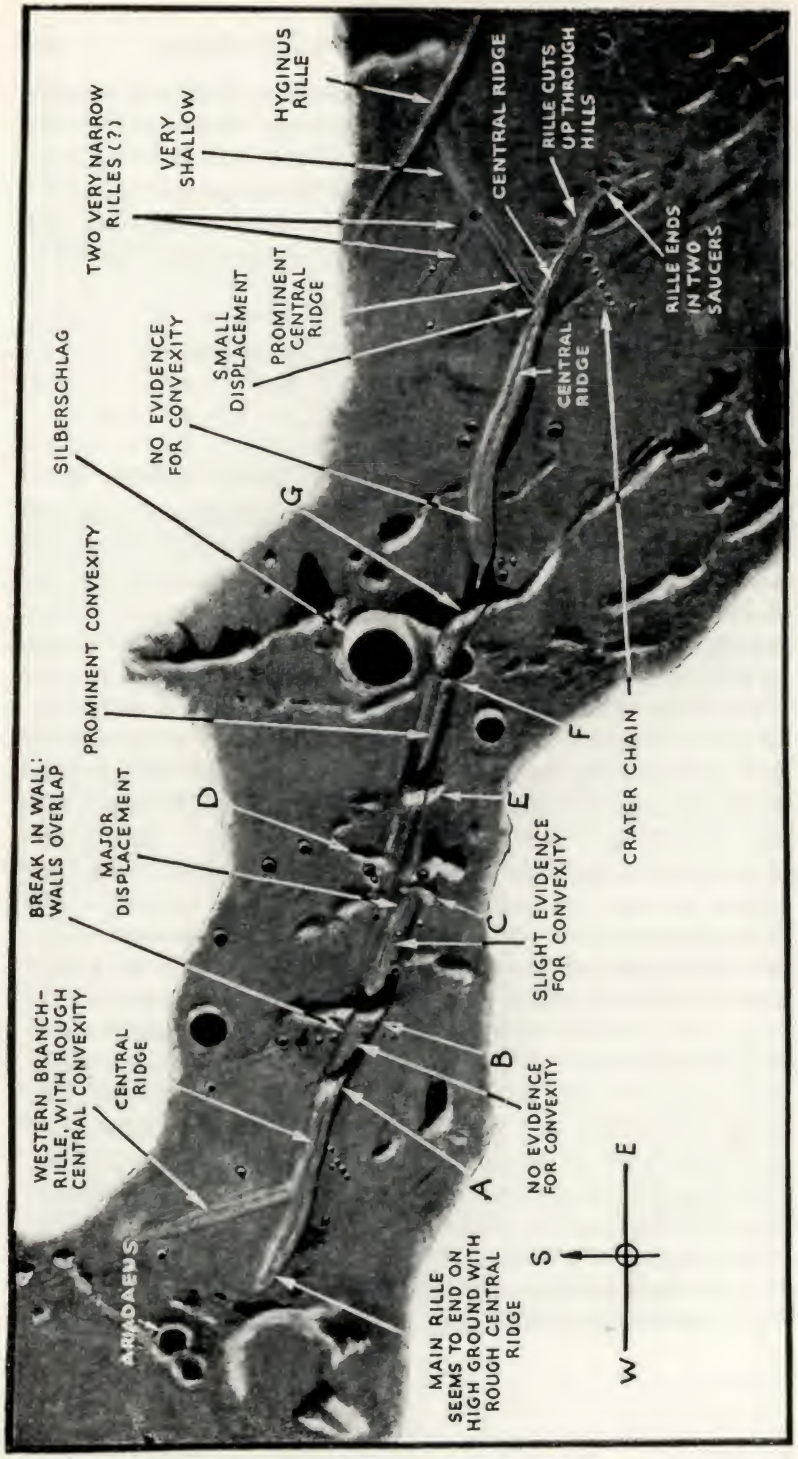

FIG. 12-2-4. The Ariadaeus Rille and branch rilles: drawing by Fielder, based on observations made at the Pic-du-Midi Observatory

(b) The Rille shows direct evidence of having a convex bottom, or central ridge, along most of its length. Sometimes this appears to be a "smooth" convexity, as in the stretch between *E* and *F*, sometimes it appears to be a steeper-sided ridge, as in the part just west of *A*, or in the eastern branch-rille, and yet again it sometimes appears to be a very rough (blocky) longitudinal swelling, as in the extreme western part, and in the western branch-rille.

(c) The Rille is not continuous: there is one major displacement, at *C*, where two parts of the Rille run alongside and end in hills, and there is at least one smaller displacement at the point where the eastern branch-rille joins the main Rille.

(d) There are several cross-ridges, lettered *A*, *B*, . . . *G*. These form parts of the ringwalls of old craters, and the cross-ridges belong to the family which is quite pronounced in the neighbourhood of the Rille.

(e) The cross-ridges generally throw concave or fork-shaped shadows over the bottom of the Rille. If the parts of the ridges which are throwing these shadows may be considered to be horizontal, then the concavity of each shadow may be taken to indicate a convexity of the Rille-bottom.

(f) Ridges *B*, *E* and *G* have what appear to be narrow "passes" through them in their northern sides and "saddles" or broader passes in their southern sides, these passes running parallel to and just inside the wall of the Rille, in each case. Some of these could possibly exaggerate the apparent convexity of the Rille-bottom as determined from shadow measurements. In ridge *A* a pass could be seen only at the northern side of the Rille. One of these passes had apparently been noticed by Klein (1899b) who wrote about a "crack" which he had seen near to the north bank of the Rille, through a transverse "sickelform" ridge at the east side of Silberschlag. He was undoubtedly referring to ridge *G* in Fig. 12-2-4: this contains the most conspicuous of the passes. These passes gave the clear impression that the parts of the ridges crossing over the Rille had tops which were slightly humped rather than perfectly flat, and that they had dropped away from the remaining parts of the ridges on the land to either side of the

Rille. The phenomenon of isostacy might be used to explain these observations.

The notes given above bear closely upon the problem of the origin of the rilles in general, and the problem will be formulated in 12-4.

The next question to ask is whether other rilles display similar phenomena. Whitaker (1956b) has gained the impression that the portion of the rille in Janssen which is nearest to Fabricius has a cross section as shown in Fig. 12-2-6a. On the other hand, Warner (1956c) has been led to believe that a section of the Janssen rille might take the form of Fig. 12-2-6b. Possibly in support of Warner's

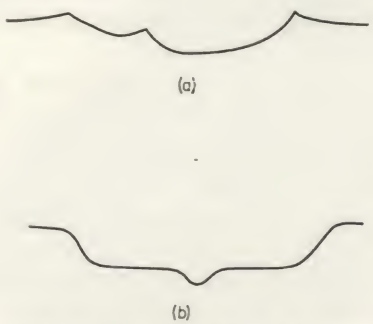

FIG. 12-2-6. Possible profiles of a rille in Janssen, according to (a) Whitaker, (b) Warner

observation is a comment by Clarkson (1952a) that the bottom of the rille in Janssen is "like a ditch, or channel, at the bottom of a shallow valley". These qualitative descriptions serve to indicate at least that independent observers have noticed that the bottom of the (large) Janssen rille is not flat. A photograph of the rille is reproduced in Fig. 12-2-7 and, from visual observations, the author confirmed Whitaker's impression but thought that the rille proper might have been located between *R* and *W* rather than between *M* and *W*, *M* being a mountainous ridge which was casting a shadow almost as far as *R* when the observation was made. The author concluded that this part of the rille did not have a central ridge in it, but he suspected that the bottom of the rille was convex further along the rille, in the narrower part, at *K*.

By no means were all the rilles such difficult objects. Several others were suspected to show convex bottoms at the moments of perfectly

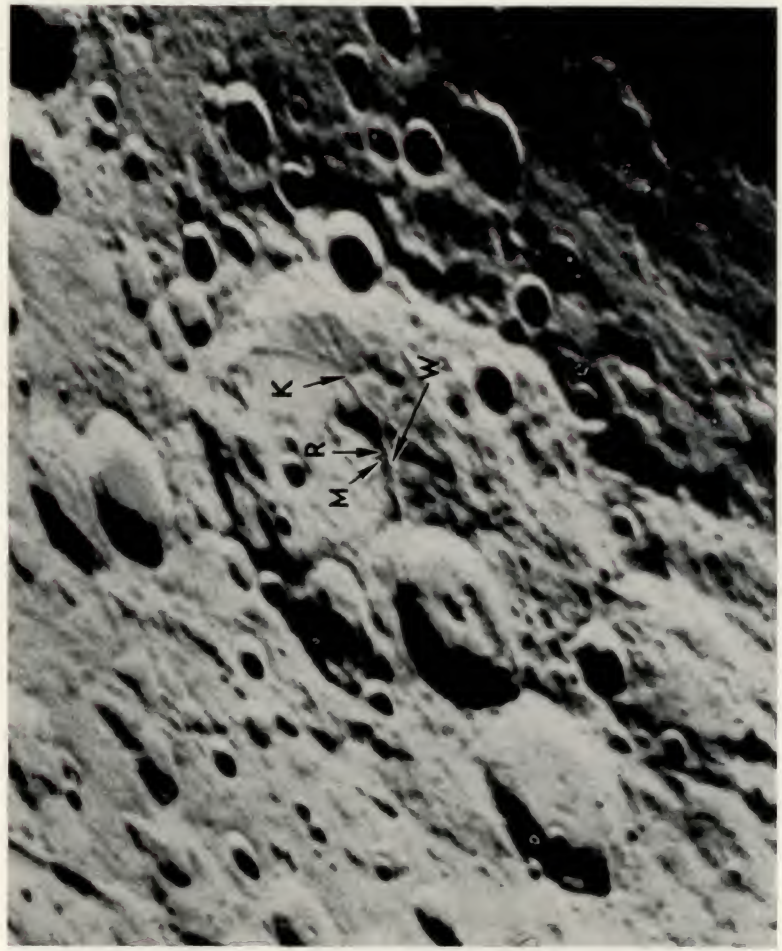

FIG. 12-2-7. Rille in Janssen

steady seeing, and between the nights of 21 November 1956, and 14 December 1956, no less than twenty-two cases were suspected, seven of which were classed as almost certainties. The results have been listed in Table 12-2-1.

TABLE 12-2-1

Approximate Universal Time	Rille	Bottom of rille	* Weight of observation
21 Nov. 56 23^h50^m	Near to Cauchy	Convex	1
24 Nov. 56 02:00	Ariadaeus, eastern branch-rille	Ridge	3
24 Nov. 56 02:00	N.W. of Triesnecker	Convex	3
24 Nov. 56 02:00	Western Hyginus	Ridge	1
24 Nov. 56 05:30	Ariadaeus, Eastern branch-rille	Ridge	4
24 Nov. 56 05:30	N.W. of Triesnecker	Convex	1
27 Nov. 56 05:00	West member of W. Mare Humorum rilles, nr. Campanus	Blocky ridge (up slope?)	3
27 Nov. 56 05:00	Same, E. of Hippalus	Convex	2
27 Nov. 56 05:00	The Hippalus rille, in mountains† to the S.	Blocky ridge	2
27 Nov. 56 05:00	Cobra Head	Short ridge	2
7 Dec. 56 19:00	N. end of Janssen rille	Blocky ridge	1
8 Dec. 56 18:00	Same part	Blocky ridge	1
8 Dec. 56 18:00	S. member of Sabine–Moltke rilles	Convex	3
8 Dec. 56 18:00	E. part of Janssen rille	Blocky ridge	2
9 Dec. 56 18:00	Most of Ariadaeus	Convex	4
9 Dec. 56 18:00	Ariadaeus, eastern branch-rille	Ridge	4
9 Dec. 56 18:00	Ariadaeus, western branch-rille	Blocky convexity	3
10 Dec. 56 20:00	Foot of Apennines	Blocky ridge	2
10 Dec. 56 20:00	Western Hyginus	Ridge	3
11 Dec. 56 17:30	East of Birt	Ridge	1
13 Dec. 56 21:00	In Gassendi	Ridge	3
13 Dec. 56 21:00	The Hippalus rille, in mountains to the S.	Blocky ridge	3
14 Dec. 56 20:00	S.E. from de Gasparis	Convex	3

* Weight 1 Possible
2 Probable
3 Very probable
4 Certain (observed more than once)

† This part has been drawn by Schmidt as a crater rille.

Together with the observation of the Ariadaeus Rille on 15 June 1956, described earlier in this section, Table 12-2-1 lists only the observations which have been made so far by the author. It is most interesting to find that Klein (1899a) said that the part of the Hyginus Rille which runs more nearly west to east was not a valley, but contained "several . . . bright striations appearing either as elevations or depressions along the bottom of the Rille". Evidently Klein had noticed the central ridge, but was unable to decide whether in fact it was a ridge or a depression. Up to date, the author has come across no other literature on this subject, but Cooke (1956d) has drawn in the "Cobra Head" a ridge which may well be of significance. The author could find no evidence whatever for a ridge running inside any other parts of the Herodotus Rille. Although Pickering (1908) did not explicitly mention a convex bottom, he noted "several minute craterlets" in the bottom of the Ariadaeus Rille, and wrote, "Evidently like our dikes and mineral veins it has been partially filled from below".

A significant number of rilles have now been seen to exhibit the phenomenon of internal longitudinal protuberances. In scores of cases the bottoms of rilles were seen quite clearly and it would be very illogical to conclude that still narrower rilles would be deep cracks. Rather, it seems to the author that all the normal rilles must be of common genesis and that the depth of a rille must, *in general*, be only a fraction of its width, so that the features which look most like cracks must be, in fact, the shallowest. This follows from even a small extrapolation of the data now at hand.

Only a few estimates of the absolute dimensions of the rilles have been made. Schmidt (1856) said that the rilles were, in general, between 4 and 20 *Meilen* long (1 German Meile $\simeq$ 5 English miles $\simeq$ 7·4 km), 300–2000 *Toises* broad (1 French toise $\simeq$ 6·4 English feet $\simeq$ 1·95 m) and 50–200 toises deep. The conversions give, for typical dimensions, 30–160 km long, 590 m–3·9 km wide, and 100–390 m deep. However, ten years later, Schmidt (1866) found the depth of the south part of Schroeter's Canyon to be 260 toises (510 m). The author's measurements yield 590–1160 m for the depth of the Ariadaeus Rille at a point between ridges *D* and *E* in Fig. 12-2-4 and a width of some 5 km at the same place. These values agree very well with Pickering's (1908): he wrote, "The Ariadaeus rille . . . measures three miles [5 km] in breadth by a little over half a

mile in depth [>800 m], as determined by the shadows of the ridges that cross it in various places." We can certainly say that the depths of the rilles are probably always but small fractions of their widths.

There is a common belief that the walls of even normal rilles are in general elevated above the surrounding country. That crater rilles had clearly raised walls would not be surprising, and, correctly, Klein (1899a) so described the walls of the crater rille between Copernicus and Eratosthenes. (But this might rather be thought of as a crater chain.) However, Smith (1948) maintained that normal rilles sometimes had raised walls. Of the major rille in Petavius, Wilkins and Moore (1955b) wrote "In places this . . . has raised banks . . ." On the other hand, Weinek (1894) wrote "Both borders of the great rill appear hilly . . .", and this, too, has been the impression of the author, who knows of no concrete evidence that the walls of normal rilles rise above the general level of the surrounding terrains.

12-3. The associations of rilles with faults and ridges

In the east of Mare Humorum there is an impressive system of rilles and ridges, as shown in the chart of Fig. 12-3-1. Some of the ridges are wrinkle ridges, but all these features exhibit approximate parallelism along the shores of the Sea. There is also an impressive fault-like feature which, however, finishes as an ordinary ridge at both ends and, in the author's opinion, does not reverse direction, as has been suggested by Whitaker (1956e). Schmidt (1866) has drawn a good chart of this area and he showed the fault as a ridge, ending, at the south end, as two ridges, in better agreement with the author.

The difference in the altitudes of the land to either side of the Burg fault, which runs approximately parallel to the family which intersects the Alpine Valley and the Carpathian Mountains, becomes less and less as the fault trends northwards. But just as it becomes apparently vanishingly small, the fault is continued, in the same straight line, as a *rille*, and, according to Smith (1948), Trouvelot ("Murs Enigmatiques Observés à la surface de la Lune," *L'Astronomie*, 1885) thought that ridges often ran into rilles. The approximate parallelism of the Straight Wall and the rille associated with Birt may be of significance. Rilles near to Cauchy connect with *each* end of the

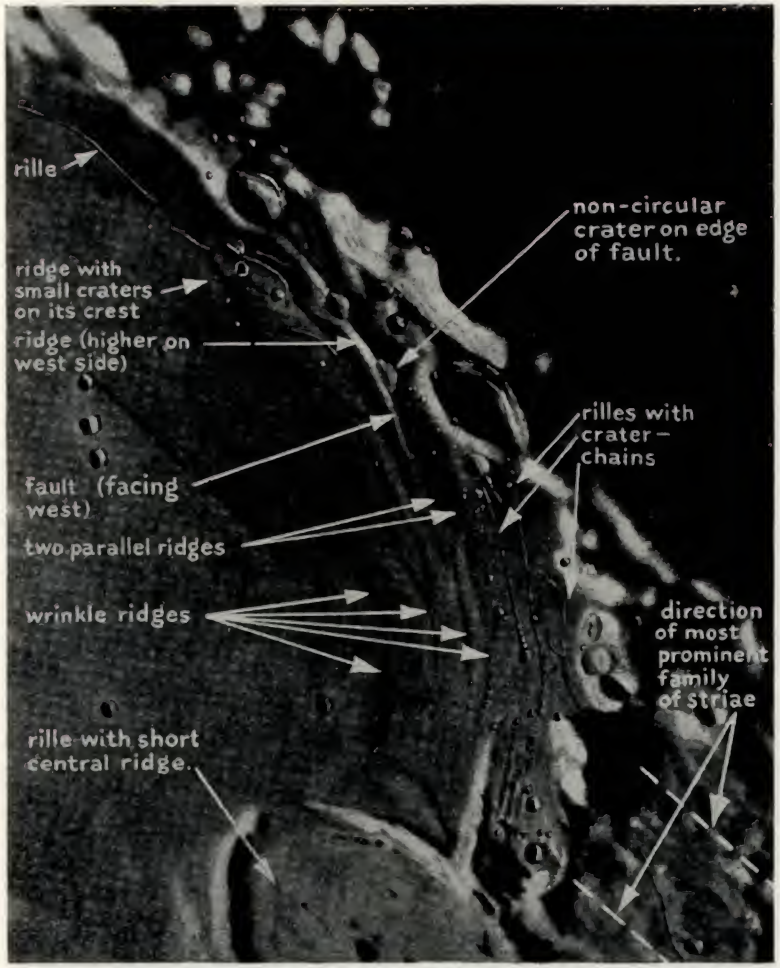

FIG. 12-3-1. Rilles, ridges, and the well-known fault in eastern Mare Humorum: carbon drawing by Fielder, based on a photograph taken at the Pic-du-Midi Observatory

fault* in that area. The well known central ridge in Alphonsus has a companion normal rille/crater rille running along its eastern feet and this rille continues in the same straight line inside the east wall

* At least, Krieger (1898) shows this as a fault. The formation is very wide, and the author suspected it to be a wide rille with a convex floor (see Table 12-2-1). Arthur (1959a) drew it with the 40-in. Yerkes refractor, and believes that it is a *double* fault.

of Ptolemaeus. In Bonpland, Parry and Fra Mauro (see Fig. 11-3-2) there are rilles which are parallel to ridges in the vicinity.

Many other similar associations could be quoted.

12-4. On the origin of rilles

In Baldwin's (1949) opinion, "... rills are intimately associated with the birth processes of the maria". And, "Because the rills are subsequent to the maria and yet are so clearly associated with their shores, some characteristic of the lava flows seems to have been the cause of the formation of these cracks." He suggested that large blocks of the Moon's crust sank and that the rilles developed in the pivotal areas.

Let us consider more carefully the detailed structure of the ridges which cross the Ariadaeus Rille. At least some, and probably all, of these form parts of the ringwalls of ruined craters. Some of the ridges pass right across the Rille continuously (though not with constant altitude). If these ruined craters had been formed after the Rille, then, clearly, the Rille would have been effaced within the walls of the craters. This is not so, and, indeed, the Rille looks as if it is a much younger feature than the craters. Therefore, the craters must have formed before the Rille itself was formed. If the Rille had been the result of a splitting open of the crust, then the cross-ridges would have split apart and gone with the crust. Hence, since the ridges continue across the Rille, it is believed that *the Rille cannot represent a crack* which has been more recently partly filled with lava, as Gilbert (1893) and Baldwin (1949) have suggested. If we assume that all the rilles are of the same general form as the Ariadaeus Rille, it seems as if we must look for some other way of explaining them.

When rilles cut up through mountains the bottoms always appear to be very roughly sculptured, strewn with innumerable rock blocks. On the other hand, the forms of rilles crossing marebase materials usually appear to be smooth, and the walls of these rilles appear to have small, uniform slopes. The author has traced the prominent rille which runs near to the feet of the Apennines, and parallel to the scarp face, across Palus Putredinis at the place defined by the intersection of the rille and the line which joins Conon to the western wall of Archimedes (see Fig. 12-4-1). The rille continues in the lunarite to either side of this tongue of marebase material, but, whereas it is

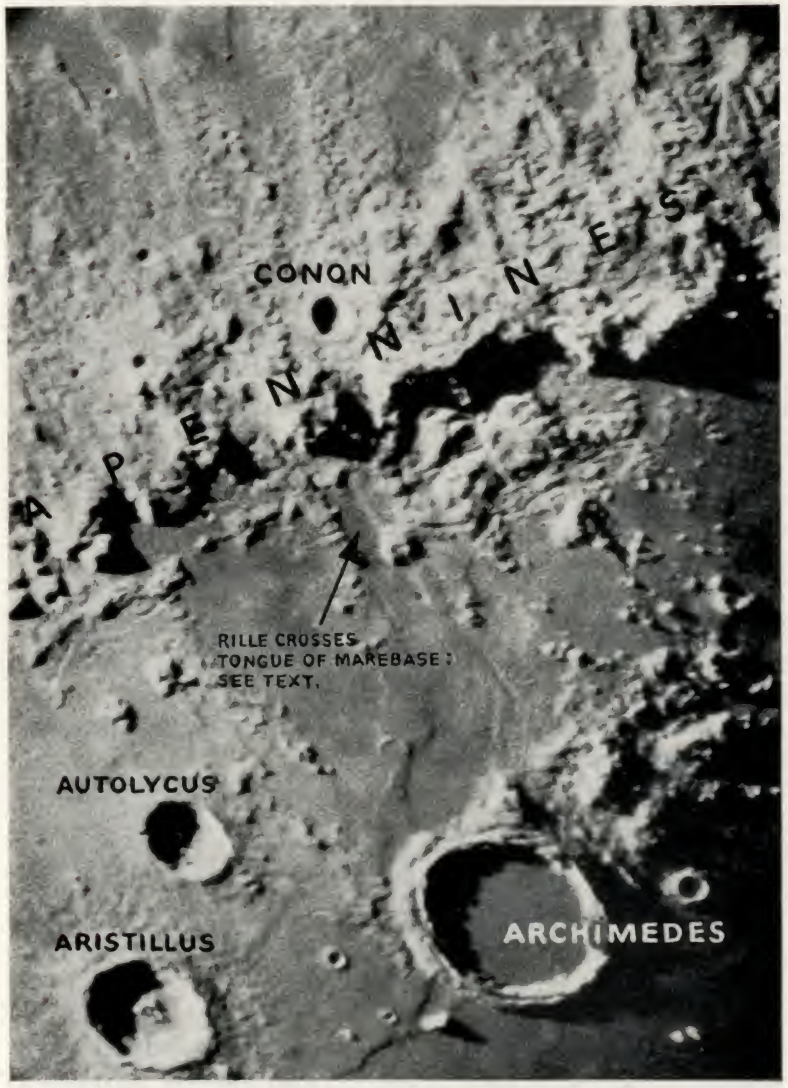

FIG. 12-4-1. Rilles at the feet of the Apennines: possible evidence of erosion

clearly defined in the lunarite, with hard, angular features, the rille is a difficult feature in the lunabase, being less deep and apparently "smoothed out". It may be assumed, of course, that these differences

may be due to erosion, but it would seem incredible that the products of erosion would not collect also in the highland pockets which must surely exist.

The following preliminary idea of the origin of the rilles has so far been developed only qualitatively. A release of pressure occurred at some depth in the Moon. (That this process must have operated is evident in view of the great amount of faulting which has occurred.) This caused local melting and an appreciable increase in the volume of the material ensued* which was forced—partly by hydrostatic pressure—up fractures marking planes of faulting, and which began to crystallize during the ascent, with stoping and widening of the magma chamber.†

In the case of normal rilles, the melt undermined the fragmentary surface layers, causing them to subside and produce rilles much wider than the original fractures. However, in the case of crater rilles, conditions in the melt were such that crystallization resulted in the confined accumulation of high pressures in the water vapour phase. These high pressures were released by explosions which produced craters within the rilles. Urey (1957) has envisaged a similar type of mechanism for the crater rilles, and has correctly pointed out that craters produced by igneous explosions would probably be indistinguishable from meteoritic explosion craters. Pickering (1908) noted that crater cones occurred on cracks in Kilauea "much the same as crater pits do on the Moon". Klein's (1899b) belief that the normal rilles and the crater rilles have evolved along very different lines is not supported. The author's theory has been expressed more fully elsewhere (1960), but the notion that the rilles are subsidence features—and not cracks—is considered to be an observational fact. Thisc onclusion was reached before Kuiper (1959b) published a statement that the Ariadaeus Rille is a *graben* feature, and it is very pleasing to find agreement on this point.

Returning to the Ariadaeus Rille it is seen that, had the viscosity of the melt been such that it would not support the cross ridges, some slumping would have ensued, as observed. The convexities and central ridges within the normal rilles are thought (1960) to have

* Yoder (1952b) has quoted 0·033 $cm^3\ g^{-1}$ for the volume change involved in the melting of diopsode.

† See Daly (1933) for a description of the possible processes involved in the ascent of magmas.

arisen as a consequence of the pressure of the rising magma acting on the overlying materials.

The ascending magmas should have risen to greater altitudes in mountainous regions than elsewhere, but the narrowing and rough nature of rilles in such regions could be explained by a weakening of the underlying structure and the consequent settling down of solid blocks of rock.

Many, though not all, of the characteristics of rilles have been accounted for in the foregoing discussion. The association of rilles with faults has been explained satisfactorily, but the notion has emerged that the rilles themselves are not indicative of a surface-tensile phase of the Moon's history, as has been believed up to date.

12-5. Wrinkle ridges

In contrast to the linear ridges, these are apparently smoother, snaking elevations. In general, they are longer than the linear ridges, and are to be found on the marebase, particularly around the borders of maria. Often they exhibit approximate parallelism. Baldwin (1949) has maintained that they are ancient flow marks. If this were the case, one would expect to find appreciable differences in the levels of the country to either side of a wrinkle ridge. The author has been unable to find any decisive qualitative evidence for the existence of such differences. Profiles of wrinkle ridges have been drawn in Figs. 2-3-7a and 2-3-7b. Clearly, the top of one is complex, and not of uniform curvature. Visual examination of other large wrinkle ridges, under excellent conditions, has shown that there may be two or more parallel crests, like minor mountain chains lying on top of a broad mountainous base. Such phenomena do not seem to support the hypothesis that the wrinkle ridges are solidified waves of lava or of dust. The author's measured section has shown that the wrinkle ridge on the eastern side of the gap between the Apennines and the Caucasus has an altitude of the order of 200 m, and that the width of its base is of the order of 16 km. The author has performed measurements of the slopes at various points along two typical wrinkle ridges: the slopes are of the order of 1° and do not seem to exceed 5°. In many cases, wrinkle ridges appear to be coincident with the walls of old craters.

Kuiper (1959b) believes that several wrinkle ridges have cracked open along their crests, and that the cracks are often filled with

light-coloured rocks which resemble extrusive dykes. When these dykes are of sufficient width they can, he says, be seen to have somewhat rounded tops. Kuiper considers the wrinkle ridges themselves to be compression features. The author finds it difficult to comment on these views, but suspects that rilles, faults, and wrinkle ridges have associated origins. Thus, the magma which, it has been suggested, rises to form a rille might, under different conditions, produce a wrinkle ridge, instead.

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CHAPTER 13

Crater Distribution and Frequency

13-1. The spatial distribution of maria

Roughly speaking, the surface of a typical mare is shaped like that of a spherical cap, but its boundaries tend to be polygonal rather than circular. Lamech (1934) wrote "... seas and craters very clearly assume polygonal forms. Their walls are, in general, oriented in preferential directions characteristic of the region in which they are situated". Darney (1950) has also noted the very large number of polygonal forms, including Mare Crisium, Mare Imbrium and Mare Serenitatis. Oceanus Procellarum is probably a composite formation, like Mare Tranquillitatis. The latter appears to consist of two overlapping maria.

The total area of marebase material north of the Moon's equator is of the same order as the total area south of the equator. No mare extends across the poles of the Moon. The original distribution of maria may have been altered by encroaching lunarite (that is, by the formation of large craters after the formation of maria); in particular, the original border of Mare Nectaris would seem to have been coincident with the Altai scarp, but this mountain arc has a much larger radius than the present radius of the Mare.

Whitaker (1956a) has pointed out the approximate symmetry in the distribution of maria about a great circle running through the SSE. and NNW. points. It has also been observed that, when the Moon is in its position of mean libration, no mare passes across the limb. It is difficult to comment on the significance of such relationships. However, there appear (Fig. 13-7-1) to be very few maria on the hemisphere of the Moon which is averted from the Earth (13-7). Had the maria been tidal lava flows, one would have expected more maria on the other side than are now observed. Since there are, altogether, relatively few maria, their observed distribution can be accommodated by assuming that they are impact scars. This does

not prove their impact origin; any maria on the other side of the Moon may be masked by encroaching lunarite.

13-2. The frequency of occurrence of craters of different sizes

Fauth (1907) measured and listed the diameters of many craters, and a curve which appears to be a rectangular hyperbola may be obtained by plotting the mid-value of a chosen diameter-grouping against the number of craters within that grouping. The data given by Fauth are inadequate for any but a sketchy analysis, but the first part* of Arthur's (1951) detailed catalogue, and the whole of Young's (1953a) catalogue (which excludes craters less than sixteen km in diameter) yield similar curves. The number of craters in a given diameter grouping increases as the mean diameter of the grouping decreases. Craters smaller than 1 km or so in diameter cannot be charted accurately even under the best conditions, and, in fact, our knowledge of the number of craters smaller than a few miles across is incomplete. Arthur (1953c) has catalogued the diameters of small craters in Mare Imbrium, and, plotted by themselves, these too lie on a hyperbola. Plotted as a straight line, the relationship indicates that there can be no crater greater than about 17 km in diameter in this particular family of craters. Small craters in seas may therefore form a class of their own.

Concerning the distribution of craters greater than 160 km (100 miles) across, but excluding maria, it is safe to say that they seem to favour limb regions. Two exceptions are numbers 1212 and 1219 of Young's Catalogue, which lie in the third (south-eastern) quadrant of the Moon: this quadrant has a noticeable excess of large craters over each of the other three quadrants. However, maria have often so influenced the appearance of large craters that this result may not be significant. It is surprising, however, that the high lunarite of the fourth quadrant bears no conspicuous craters which have diameters exceeding 160 km.

13-3. Anomalies in the frequency distribution of craters

MacDonald (1931) noticed that, if the number of craters, N, was plotted against the mid-value of the diameter-range, Δ, the resulting curve was clearly hyperbolic. Using Fauth's (1907) data, he found

* The Catalogue had not been completed at the time of writing.

that the slope b of the curve of $\log_{10} N$ against $\log_{10} \Delta$ (Δ measured in miles) was 1·9. Young's (1953) data* are much more adequate, and Young (1940) found that b was not constant: for craters up to 40 km (25 miles) in diameter he found b to be about 2, but for larger craters Young concluded that the value 3 provided a more suitable fit of the observations. Using Young's data, and taking arbitrarily two mile diameter-groupings for craters between 20 km (12 miles) and 80 km (50 miles) in diameter, the author confirmed his result that the discontinuity in the slope of the curve occurred around the value $\Delta = 40$ km.

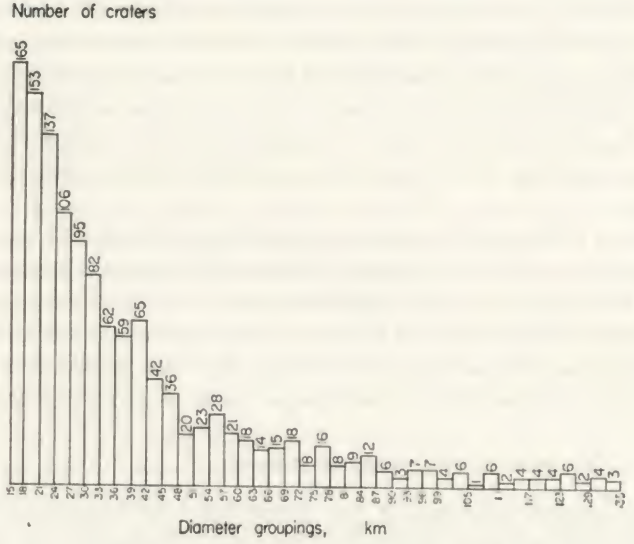

FIG. 13-3-1. Histogram based on Young's data

Young (1940) discussed the periodicity of the residual numbers and found peaks at $\Delta = 21$ km (13 miles), 32 km (20 miles), 40 km (25 miles) and 56 km (35 miles), and an unusually small number of craters at $\Delta = 18$ km (11 miles). A histogram (Fig. 13-3-1) has been constructed from Young's measurements and a glance at this

* Young listed only "craters greater than ten miles in diameter and within 70 degrees of the centre of the disk and named craters outside these limits". In order to include the whole lunar surface, the number data may be multiplied by about 3.

shows that the peak at 40 km (25 miles) is certainly very prominent. This may be significant when considered in connection with the change of slope discussed above.

Taking a different approach, Türk (1924) plotted the number of craters with, and without, central mountains and parasitic craters, against their diameters. The maximum number of craters with central mountains and parasites was found in the 25–35 km diameter grouping, and the minimum number was realized in the 40–50 km grouping. Türk also charted the density of craters—the number of craters per unit of surface area—and concluded that there were strips of equal density which emerged radially from a centre ($\lambda = +29°$, $\beta = -61°{\cdot}5$) in the southern continent. Türk noted that the lines of 85 double craters fitted in with this system—a result of doubtful significance—and that the centre of the system was located in the highest part of the surface. The latter observation was, however, based on Franz' map of absolute altitudes. There is now a better map (Fig. 3-1-1), and this shows that Türk's observation is wrong.

Arthur (1954) performed some interesting statistical tests upon the distribution of the lunar craters, and he concluded that there was no basis for arguing that the distribution was not a random one, with the exception, however, of the post-mare craters in Mare Imbrium. In the latter case, however, he thought that the distribution might have been influenced by secondary ejectmenta from Copernicus.

13-4. The spatial distribution of craters

The surface materials of the Moon may be classed as either lunarite (the brighter continental regions) or lunabase (the darker regions). Large well-formed craters occur more frequently in the lunarite. Ghost craters have long been known* to exist in maria; ghosts are ill-defined, low-walled craters, and there is a growing impression† that maria are covered with such craters, the walls of which might be linked with the wrinkle ridges. It would seem to be meaningless to discuss the spatial distribution of craters unless one were to consider the ghost craters, and the problem of the overlapping of craters.

* See Elger (1896); Smith (1898).
† See, for example, Firsoff (1957a).

There are few clear cases of a crater overlapping a smaller one; Maurolycus provides the most noticeable case. Even if all craters had been formed at random a situation such as this would not have been commonplace, for the formation of a large crater would always tend to obliterate a partially-overlapped smaller crater. Young (1940) made the proposition that a small crater of radius r_1 would have been totally destroyed by a larger crater of radius r_2 if the centres of the craters had been separated by a distance x, where

$$x < (1{\cdot}2r_2 - r_1). \qquad (13\text{-}4\text{-}1)$$

When the destructive effects of shock-waves are considered, it appears that x may be increased somewhat, thus again diminishing the probability that a crater will be observed to overlap a smaller one. Lastly, with a collisional origin for the craters, blocks of matter might be projected at all angles, with velocities amply large enough to cause "secondary" collision craters to be formed. These smaller craters would, of course, originate after the parent crater had been produced, and some might thus be superimposed on it.

Experiments with explosives led the author to believe that secondary craters could be arranged linearly, and that they could have a certain minimum separation. Boneff (1936b) studied the craters down to 6 km in diameter in part of the Mount Wilson "Region of Tycho" photograph, and found that the distances between the centres of *all* the craters (taking into account their deformations) were always $\geqslant 6$ km. Supposing that this relationship held for all the surface, Boneff investigated whether or not it was due to chance, and found that the distribution did not appear to be accidental. By studying another photograph, he obtained a similar result, and he concluded that the meteoritic theory was probably not to be favoured.

Later, Boneff (1956b; 1957b; 1958), extracting data from Schurig-Götz' *Himmels Atlas* (7th edn., Leipzig, 1942), drew conclusions which were very strongly against a random distribution of craters over the whole hemisphere of the Moon, but the craters in the eastern half of the Moon's disk (that part of the Moon which leads, in its orbit around the Earth) were distributed not quite as non-randomly as those in the western half. For reasons given above, these conclusions, even if based on adequate data, do not necessarily invalidate the impact theory.

13-5. Crater-pairs

Statistical investigations of the Moon's craters are extremely difficult because of the large number of variables to be considered. Oversimplification invariably leads to results which are all too easy to interpret without careful consideration of the initial assumptions. Thus, there are many pairs of craters on the Moon, but, as some of these are twins, it would not be profitable to compute the probability that their respective components were formed independently, from random impacts. The term "twins" is applied to craters having essentially similar characteristics, such as the central mountains, the inner ringwalls and floors, the depths, and the features of the outer ringwalls. Examples are Aristoteles and Eudoxus, Aristillus and Autolycus, Agrippa and Godin, and Sabine and Ritter. If such craters were impact craters, each pair must have been formed at nearly the same time by bodies which moved with similar velocities. Why, as the mean diameter of each of the above-mentioned pairs increases, does the distance between the centres of the craters forming the pair also increase? Is it at all significant that, in each of the first three examples, the lines joining the centres of a pair are nearly lines of longitude and that the smaller component of each pair occurs to the south side of its companion crater? It is possible to ask more questions than can be answered satisfactorily.

13-6. Crater-chains

A typical crater chain may be seen just below the centre of the *Frontispiece*.

The directions of some of the crater-chains have been correlated with the directions of certain families of the grid system (11-3) and, hence, it is very improbable that these were produced by meteorites. The craters forming the chain near to Copernicus may possibly have originated when the surface there was punctured by secondary ejectmenta from Copernicus itself. The depth-diameter relationships for craters in chains do not appear to be different from those of other craters (Arthur, 1950b).

13-7. The other side of the Moon

Some 70% of that portion of the lunar surface which is averted from the Earth was photographed on 14 September 1959 on 35 mm

film contained in the Russian Lunik III probe vehicle. After automatic processing, the many negatives were scanned electronically with up to 1000 lines to the Moon's diameter, and the weak signals transmitted were detected by large antennae on the Earth. Elementary pictures which were built up by this scanning process were superimposed, in order to produce finished photographs with a minimum

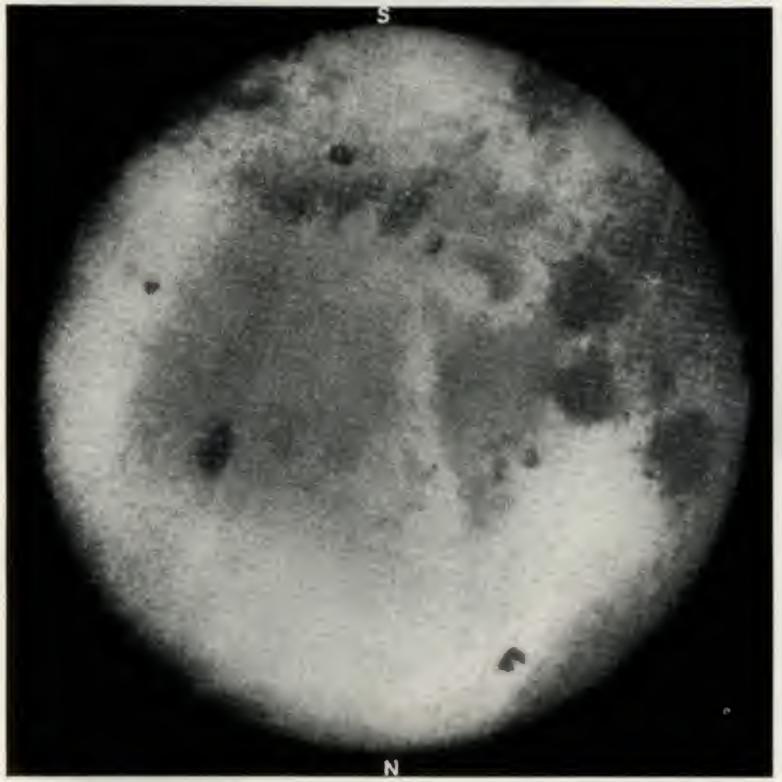

FIG. 13-7-1. The averted portion of the Moon photographed from Lunik III (1959). Part of the well-known hemisphere is also shown

of defects. Two lenses—focal lengths 20 cm and 50 cm—produced original negatives showing the full disk, and a portion of the disk, of the Moon, respectively (Figs. 13-7-1 and 13-7-2). Additional information may be found in the booklet *Soviet Moon Rockets* (1959), or in the book published by Pergamon Press (1960).

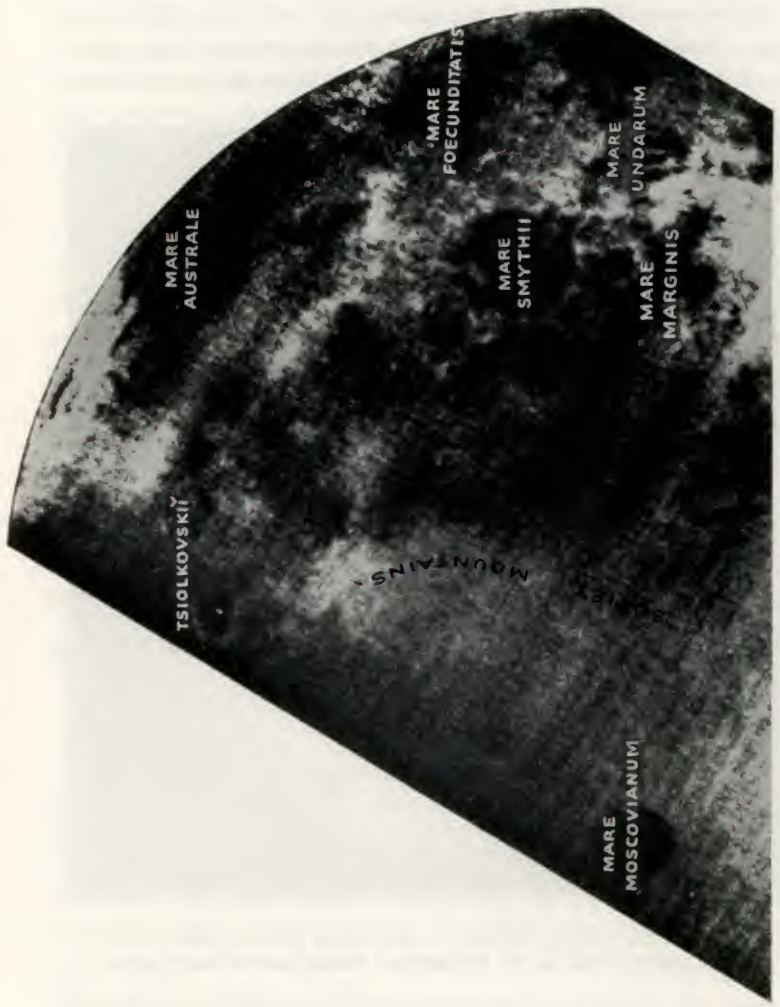

FIG. 13-7-2. A more detailed view of part of the Moon's averted hemisphere, based on photographs taken with the 50 cm focal-length lens of Lunik III

A detailed knowledge of the averted hemisphere of the Moon would be very valuable for the purposes of statistical analyses as outlined in this chapter. Partly because of the complex processes involved in obtaining the pictures, and partly because the automatic cameras were directed at a nearly "full" Moon, the quality of the finished pictures is not good.

The most surprising inference which may be drawn from these photographs is that there are relatively few maria on the newly revealed portion of the Moon. By comparison with the more familiar face of the Moon, about 30% of which appears on the Russian photographs, the bright areas on the new photographs are probably mountainous, rich in craters, and the grey areas may possibly contain large, dark floored craters.

Much may be learned from better quality photographs of the other side of the Moon. More information of a statistical nature will enable a more critical examination to be made of the existing controversial theories of the origin of craters and even of the Moon itself.

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CHAPTER 14

Conditions Relating to the Origin of the Moon's Surface Structure

IT IS not the purpose of this final chapter to discuss the innumerable books and papers which have in the past created the "crater controversy". To review a fair proportion of the works which have been devoted to the origin of the surface of the Moon would require a book to itself.

A brief general outline of five of the most plausible theories of the origin of the craters is given below. Each of these has its own exponents, but the author has disregarded these theories, and instead has given a reasoned account based on fact rather than on speculation. To aid the reader to trace the sources of the various arguments frequent references to the ealier sections of the book are made.

(i) **Meteoritic Theory.** Meteorites are even today colliding with the Moon, but, in the case of large meteorites the frequency of collisions is very small (see 11-3). When a high-velocity meteorite collides with the Moon, a crater is blown out explosively by the sudden transformation of energy. A circular crater will result almost independently of the angle of impact. Central mountains are assumed to have been produced (a) by volcanic action induced as a result of the impact, (b) as a consequence of the elastic recoil of compressed substrata or, (c) they may simply be a part of the original surface not excavated by the explosion.

(ii) **Generalized Impact Theory.** This assumes that, in addition to high-velocity meteorites causing explosion craters on the Moon, low-velocity objects—possibly of asteroidal sizes—also collided with the Moon and broke up on impact. The craters produced by low-velocity objects would not necessarily exhibit circular symmetry, and such impacts could generate some local melting of the rocks. Maria are supposed to be of impact origin. Secondary ejecta could make fresh craters or grooves, and central peaks could be produced in ways similar to those described in (i).

(iii) **Volcanic Theory.** Volcanic activity of the Vesuvius-type built up crater-ring walls by the symmetrical ejection of materials, which led to subsidence of the crater-floors by the mechanism of ring-faulting. Dying activity sometimes produced central cones and, on other occasions, blew out parasitic craters on the floor of the main crater.

(iv) **Igneous Theory I.** Lavas periodically ascended from subselenian magma chambers and solidified in gentle slopes on the surface of the Moon. (Hawaiian-type of igneous activity). Crater-walls became higher during each extrusion in which the lavas passed their previous highest level, the lavas usually retreating again after every such resurgence. The motion of the lavas may have been associated with the tides raised by the Earth. Central mountains could be built up in the same way as in the case of terrestrial ash cones; and parasitic craters, of saucer-form, by collapse.

(v) **Igneous Theory II.** Laccoliths, or similar sill-type intrusions, are assumed to have arched the Moon's surface at various places to form domical uplifts. The domes are assumed to represent embryo craters, and true craters are formed by (a) the collapse of a dome (caldera-type craters) or (b) explosion, initiated by high internal pressures (crypto-volcanic-type craters: see 12-4.)

A selected bibliography of the literature has been recorded at the end of this chapter, but no attempt has been made to refer to any of the works which have been listed there.

14-1. Erosion and the time sequence of the topographical features

According to Ebert's Rule (2-3), the ratio of the depth, δ, of a crater to its diameter, Δ, decreases as the diameter increases. MacDonald found the relationship

$$\delta = k\Delta^{\frac{1}{2}} - c,$$

where k is a constant. The fact that the quantity c was found to be a variable indicated that the crater-bottoms did not arrive at their present levels by uniform magmatic extrusions. Furthermore, c did not vary *irregularly*, which proved that the craters had not been flooded by means of extrusions arising from localized sources. The variation of c as a function of Δ could possibly be explained by accepting a process of erosion which operates in such a way that the larger the crater, the more has it been filled in by the erosional products.

Now the lower limit of the diameters of the polygonal craters seems to be about 20 km (11-3). If the grid had developed before the larger craters, then one would have been forced to conclude that the craters' boundaries developed under restrictive conditions. However, there is clear evidence that the lattice patterns came after these craters (11-4), and there is no reason to suppose that the grid came before them. Certainly, the valleys in the Ptolemaeus regions provide very clear evidence that they came later than all the large craters through

which they pass (11-2) and, although it has been shown that these valleys might possibly have been produced by projectile-action (11-2), it has also been seen that they are intimately associated with the grid system. Again, many rilles, which are known to be associated with the grid system (12-3), are clearly younger than craters of diameters in excess of 20 km (see 12-4, and Fig. 11-3-2). Therefore, it is more reasonable to suppose that the craters larger than 20 km or so were modified to polygonal forms, after formation.

Craters less than about 20 km in diameter were formed after the grid system (11-3), since these craters are apparently non-polygonal and are otherwise undistorted by other features.

Clearly, the visible small craters which are embedded in larger craters came later than the larger craters.

All the above observations may be accommodated if we suppose that the largest craters on the Moon came first and that, since that time, the tendency has been for progressively smaller craters to form.

The fact that the maximum inner slopes of craters decrease as the diameters of the craters increase is therefore suggestive of the fact that there is a process of erosion in operation.

So far as can be ascertained, the rays cross over all other features (10-1) and must therefore be among the most recent acquisitions of the face of the Moon. It does not follow that the rays are *the* most recent topographical features, however, because it is likely that they were flung out at the time when their craters of origin were excavated and, for the major ray systems, these craters have definitely suffered modification under the stresses of the grid system. Since the displacements of the Moon's outer shells have been localized, and are only of the order of the widths of rays, then it follows that the rays may well have been deposited before the grid system played havoc with the craters.

Old craters do not show rays. This suggests that the rays themselves are subject to erosion (10-3). It is possible that they darken as time elapses. The inner walls of most craters are brighter than their floors. Because both the walls and the floors of craters darken as their diameters increase (and therefore as their ages increase), the process of erosion would appear to yield a product which is darker than the original material. The brightness of the uneroded rocks varies, however, so results may only be statistical and must contain random errors. Striking changes in the reflectivities of rocks—both fairly

FIG. 14-1-1. Real differences in the reflectivities of lunar rocks: unusually dark mountains north of Hyginus

flat and mountainous—may be seen in Fig. 14-1-1. The brightest rays must have the smallest maximum temperatures in the lunar dialy cycle. If the erosional mechanism is at all temperature-dependent (this has not been proved) then the rate of erosion would be slowest in the most recent formations. Aristarchus is the brightest part of the Moon, and so this may be one of the most recent craters. In any event, craters with associated bright rays must be among the youngest on the face of the Moon.

14-2. Origins of the craters

The large craters are relatively shallow formations and their ring-walls are roughly of the volumes needed to fill them up level with the outside surface (Schroeter's Rule, 2-2). This suggests that the ring-wall of a crater is composed of materials which have been displaced from the crater in question. The outer slopes of large craters have average values which range only between the orders of 1° and 10° (2-2).

The minimum values of the steepest inner slopes of the largest craters (diameters 100–200 km) are about 30° if the craters have central peaks, and are about 26° if the craters do not have central peaks. These values increase as the diameters of the craters decrease (2-2). The smallest craters which have been measured (diameters 2–3 km), however, may have inner slopes as great as 55° (2-2). These observations, taken together with the results of 14-1, suggest that the erosional process which is proceeding is tending to reduce the inner slopes to an angle of comparative stability at 30°.

Very small craters may or may not have outer slopes. Those with raised rims are probably explosion craters, and those without raised walls may be collapse craters. The latter type of crater seems to occur, occasionally, on the marebase. The interior surfaces of small craters approximate to paraboloids (2-3) and their inner slopes are so steep that it seems that they cannot be composed of ash.

Roughly following one branch of a hyperbola, the number of craters, if plotted against different diameter groupings Δ, increases as the diameter grouping decreases (13-2). At $\Delta = 40$ km, three is an exceptionally large number of craters (13-3). Furthermore, as the diameters of craters decrease, the number of craters increases at a markedly smaller rate for $\Delta \gtrsim 40$ km. The statement $\Delta = 40$ km may therefore mark an important *time* (as shown in 14-1) in the

accumulation of craters. Craters with central peaks are most frequent in the grouping $\Delta = 25$–35 km, and are least frequent in the grouping $\Delta = 40$–50 km (13-3).

The small craters in Mare Imbrium impose an upper limit of $\Delta \sim 17$ km on themselves (13-2). This suggests that these craters are not necessarily evolutionarily related to the larger craters. There is a number-peak in the general distribution curve at $\Delta = 21$ km, and a trough at $\Delta = 18$ km (13-3). The depression at $\Delta = 18$ km may possibly be explained by the complete absence of these mare-type craters.

When rays are associated with a crater, the ray-elements do not appear to trace back to a point. Rather, they collect in a "circle of confusion" which is defined by the ramparts of the crater (10-1). This would be easy to understand if ray-craters were impact craters. Elliptical rays may also be explained on these assumptions (10-4). Since rays cross over all kinds of topographical features, including mountains, it seems very probable that they were formed from above the surface, by particle-ejections from their crater of origin (10-3). Consideration of the dark haloes, and of the ray-free regions behind obstacles, have indicated that these ray-particles were shot out at small angles to the horizontal (10-2). Elliptical rays again lend support to this conclusion. By whatever process the craters were excavated, the bulk of the material must also have been removed at angles appreciably smaller than 90°, for matter projected vertically would have dropped back to fill up the craters. The shapes of the ringwalls may most easily be explained if the materials were displaced laterally.

Consideration of the Rosse ray lent support to the low-angle ejection hypothesis, and suggested two important points. Firstly, that secondary ejectmenta of appreciable size were propelled away from large craters, to produce smaller craters (10-2; 13-4), and, secondly, that rays were composed of linear elements because they were produced from small crater beads (10-2). This leads to the notion that some small craters are secondary impact craters. In the formation of these craters, the prime mechanism may have been one of crushing, rather than one involving explosive force.

Yet again, there is clear evidence that some of the smaller craters are plutonic in origin (13-6). Thus there are probably five classes of small craters—meteoritic (or primary) impact craters, secondary impact craters, igneous craters, collapse craters, and mare-type craters. No link has been found to connect the three last mentioned classes, but it is possible, of course, that they belong to the same class. In view of these complications, it is clear that frequency diagrams would not be expected to be smooth curves.

The large craters seem to be explosion craters, and the explosions must have been centred close to the surface in order to have projected materials at small angles to the horizontal. The radial symmetry of these craters suggest that they were moulded by forces of explosive magnitudes. A number of people have observed that the energy required to excavate such craters would be of the same order of magnitude as the kinetic energy of interplanetary bodies. Although the details of the processes which Gifford, Baldwin, Gold, and others, have discussed may be wrong, large meteorites do seem to provide the most natural solution of the problem.

The central mountains of craters are highly complex masses. They do not leave the author with the same impression as that gained by Kuiper—namely, that they are of comparatively smooth outlines, as though pressed up from beneath the floor of a crater. Central mountains would possibly be left standing, in a collisional process, if the colliding body was of the order of size of the central mass, because small-scale collisional experiments yield prominent central masses. Wilkins and Moore claim to have detected a summit crater in the smaller central block of Tycho, but the author's observations at the Pic-du-Midi indicated quite clearly that this block consists of at least six, closely set, but individual, mountain peaks. Mountain-top craters certainly do exist (two may be seen in the *Frontispiece*); small craters symmetrically disposed on domes (14-5) also certainly exist; and some of these may well be igneous in origin, or they may be collapse craters.

The fact that no iron has been detected in Aristarchus (4-7) does not by itself imply that this particular crater was not produced by collision. A difficulty in the collisional hypothesis is, however, encountered in the study of the crater which lies on the edge of the fault in eastern Mare Humorum (see Fig. 12-3-1). This crater is not circular, for its centre is located on the higher (eastern) side of the fault at a distance from the edge which is less than the radius of the crater. Had the crater formed before the fault developed, a segment of the crater would have been detached from the remainder and would have been left in the low country to the west of the fault, but this does

not appear to be the case. On the other hand, had the crater been blasted out by a meteorite after the fault had developed, it would not seem at all likely that its western ringwall would remain, poised on the brink of the fault-face and so close to the centre of the explosion. Thus, a superficial examination indicates that this particular crater may have undergone what was a predominantly gentle evolution.

14-3. The nature of maria

A surprising thing about maria is that, like the craters, they have boundaries which approximate to circles but which actually tend to be polygonal (13-1). It is difficult to understand how maria originated. Comet impacts have been suggested by Kopal. Another surprising fact is that the surfaces of maria are by no means level: on the contrary, they exhibit level-differences of greater magnitudes than those found in the lunarite (3-1). Baldwin suggested that the material forming maria was lava which had flowed for vast distances. If this had been the case, level-differences of the kind observed would not have been expected (3-3). Again, wrinkle ridges do not show evidence of their being solidified flow-marks (2-3). If, therefore, the seas are composed of a rock similar to lava, then it seems that this has not flowed about very much.

Gold, on the other hand, suggested that the maria were composed of deep deposits of the eroded materials from the continents, which he supposed were in the form of very fine dusts. There is no positive observational evidence that the maria are composed of dust. If the observations (3-1) are assumed to be of sufficient accuracy to enable one to conclude safely that the bulge of the surfaces of maria is roughly of the same magnitude as the bulge of the continents, then the surfaces of maria would be as old as the continents, and Gold's idea would have to be abandoned. Accepting the observations, it seems as if the maria must have been solid at the time when the non-equilibrium bulge was formed, and that they must have remained in a non-plastic state ever since. If this were the case, a superficial layer of dust would not be excluded.

There can be very little flat, bare rock exposed on the Moon's surface (9-4). Several lines of investigation point to the presence of large numbers of unresolvable surface irregularities—possibly in the form of very small paraboloidal (2-3) or spheroidal (4-3) crater-pits,

intermixed with loose stones, all of this small-scale structure being covered with a thin layer of what is probably largely silica-dust having a grain size smaller than half a millimetre (9-4).

It is not known why the maria are so dark. Possibly, they contain more dark sulphides and black iron oxides than the continents. On the other hand, if the surfaces of maria are older than the surfaces of the mountains, the difference of albedo may be explained as being an effect produced by solar radiation (10-5).

14-4. Summary of the probable time sequence of the craters

The distortional displacements of crater-ringwalls appear to be greatest in the largest craters, and zero in craters smaller than about 20 km in diameter. This suggests that the grid-forming activity was attenuated in time and became more passive* as time elapsed, finally ceasing altogether.

Using all the facts available, the probable time sequence of the craters may be reconstructed as follows:

Largest craters. Large craters which are now without central mountains. Craters which are observed to possess central mountains. Progressively smaller craters down to those of diameter 20 km; present ray craters.	Progressive evolution of grid system.
Craters smaller than 20 km in diameter.	Grid-forming activity ceases.

It will be noticed that, in this sequence, a larger crater would not overlap a smaller one as frequently as would be predicted on the assumption of a random impact theory.

14-5. Domes and plateau craters

A picture of the domes near to Arago has been reproduced in Fig. 14-5-1. Domes are low, more or less circularly bounded swellings of diameters up to the order of 80 km (50 miles), and appear to resemble spherical caps. Several are known to possess "dome-top-craters". Domes are fairly difficult objects to detect, because their

* N. Woolf (private discussion, 16 April 1958), has correctly pointed out that, as an alternative, the activity may have been constant until it ceased.

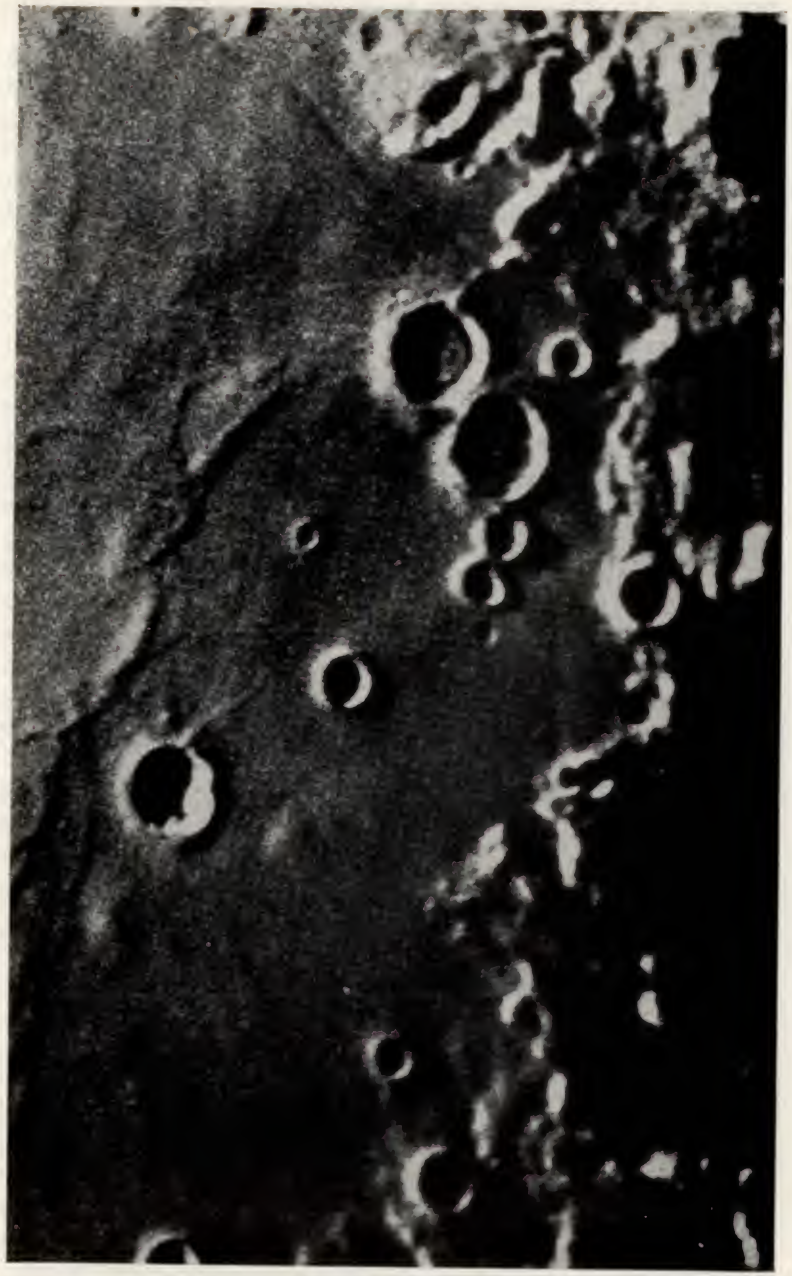

FIG. 14-5-1. Wrinkle ridges and domes near to Arago

slopes do not seem to exceed 2° or 3°, but they are probably very numerous. They are to be found, of course, only where their presence is not masked by the irregularities of the country in which they lie.

Terrestrial domes are common igneous phenomena, but Baldwin has put forward an alternative explanation for those on the Moon; namely, that they are the surface results of deep explosions. It is not easy, at this stage, to decide which of these theories should be favoured; a study of the distribution of domes may well throw some light on the problem, and there would seem to be no reason to discredit a laccolithic theory.

The most obvious of the so-called plateau craters is Wargentin. This crater is over 80 km in diameter and its bottom, instead of being depressed with reference to the surrounding terrain, appears to be raised above it, like a plateau. It is not fitting, however, to describe this as a crater which is "brim full", for the interior walls are very low or absent only along a short stretch of the circumference.

Gilbert suggested that Wargentin was filled by a splash of lava as a result of the impact of moonlets in adjacent maria, and Beard and Urey have supported this idea. The author prefers to suppose that ascending magmas filled up the crater to balance isostatically with neighbouring rock masses which were sinking. Whether or not the Moon possesses an axis, longer than average, which passes through a point close to Wargentin (3-1) it is evident that there has been faulting and a great deal of rille-forming activity to the east and south of Mare Humorum, and it has been suggested that rilles are intimately connected with igneous activity.

14-6. The nature of the forces which produced the grid system

All the ridges of the grid system are in fact merely the distorted walls of craters (11-3). Hence the ridges indicate what must be primarily lateral* movements of the surface. These lateral movements occurred in preferred directions. There are some indications that, in a given locality, movements in one direction occurred at one time, and that movements in another direction occurred at a different time, since the walls of neighbouring craters of clearly different ages ages have sometimes been modified by differently-directed stresses.

More nearly vertical movements also occurred, as is evidenced by the many selenological faults. The Rheita Valley probably lies along

* Sometimes rotational movements may possibly be involved.

a fault (11-3). (The author has only been able to confirm this for that part of the Valley which lies in the vicinity of Mallet. The plane of this fault appears to deviate but little from the horizontal.) Oblique ridges across the Valley indicate strong compression in another direction. A similar relationship holds in the environs of the Straight Wall, which, incidentally, again has a face which is by no means vertical. These faults may be overthrusts.

The crustal displacements were often accompanied by what has been suggested to be the spontaneous explosion of rapidly crystallizing magmas. Such activity is thought to have been local, only, and to have resulted in chains of small craters running parallel to fracture-lines. Local melts may have accumulated, beneath the surface, as a result of pressure reductions following the excavations of large craters.

Rilles frequently follow the grid-lines (11-3), but also frequent the interior borders of maria and of large craters. In the second case they occur alongside mountain masses. If there have been any isostatic adjustments of such mountain masses, then it is possible that the rilles developed along vertical fracture planes. On the other hand, when the rilles lie in a family of the grid, they occur alongside ridges which are clear indications of thrusting. Independent observations (12-4) have already shown that the rilles do not provide evidence of the splitting open of the surface of the Moon, and the linear ridges are essentially superficial phenomena. Hence the fact that rilles and ridges occur together in the same family leads to a perfectly reconcilable situation. It follows that, if the rilles developed along fracture planes, then the fractures did not arise because tensions predominated; rather, the rilles may follow shear fractures.

In conclusion, the whole grid system appears to have been formed by forces which operated very uniformly for long periods of time, the forces being primarily compressional in nature and possibly becoming smaller in magnitude as time elapsed. It is suggested, preliminary to further investigations, that these forces arose as a consequence of the slow adjustment of the Moon's figure in an attempt to assume the form of minimum potential.

After three and a half centuries, quantitative study of the Moon's surface is slowly emerging to provide us with the basic facts which are very necessary to have in order to construct a comprehensive picture of the history of the Moon.

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APPENDIX I

Sources

HEREUNDER will be found a bibliography which is thought to be adequate in so far as it introduces all the basic lunar topographical problems.

In the list of texts, the books of most authors are straight-forward descriptions of the Moon's surface topography, and are nearly always illustrated with charts and drawings. Theories of the modes of origin of the surface features are occasionally presented, such as the igneous theories of Puiseux (1908) or Spurr (1944; 1945; 1948; 1949a), and a large mass of evidence in favour of the impact theory was marshalled by Baldwin (1949).

Charts and drawings are sometimes of use, but should never be used as reliable sources of information. Photographs of the Moon can provide reliable data, since the errors involved can be computed. Charts and drawings of the Moon are subject to personal errors which are difficult to estimate, and hand-drawn maps are often grossly in error. For this reason, only a very abbreviated list of maps and drawings has been given below: a full list of lunar maps will be found in the text of the book by Wilkins and Moore (1955).

Of interest is Schmidt's (1878) map, in which the relative slopes of the land are indicated roughly by means of line-shading, the denser shadings corresponding to the greater slopes. Also, the relative intensity of the surface is indicated in an arbitrary scale of degrees, 0° representing black and 10° corresponding to the brightest spots on the Moon's surface. A wonderfully detailed map of the Moon is now available as a result of the life-long labours of the selenocartographer Wilkins (1946). This map has been revised, reduced in scale, and incorporated in the work of Wilkins and Moore (1955). It has also been bound in convenient form (1960a).

Progress reports of the work of members of the Moon Committee of the Carnegie Institutions of Washington will be found in the

Carnegie Year Books from 1927 to 1939. The Committee clearly appreciated that the only reliable map of the Moon's surface features would be a photographic map, and elaborate techniques were developed to produce such a map. His discussion on the poor state of lunar nomenclature and of the consequent difficulty of describing the positions of objects exposed upon the Moon's surface, led Saunder (1905) to a similar conclusion: he suggested that photographs be published with superimposed réseaux. G. P. Kuiper and his colleagues at the Yerkes Observatory have now completed a lunar photographic atlas (1960b) of the best quality possible at present; and the second part of this atlas fulfils Saunder's suggestion.

Pickering's (1903b) photographs are of poor quality but have the advantage of showing a given region at different times, these times being so chosen that the angles of vision and the librations vary considerably. As the Kuiper atlas also does this, Pickering's atlas is now of very limited use.

The best lunar photographs of today have been taken from the Pic-du-Midi Observatory (24-in. f/30 refractor), the Mount Wilson and Palomar Observatories (100-in., f/16·1 reflector, in particular), the Yerkes Observatory (40-in., f/18·6 refractor), the McDonald Observatory (82-in. reflector), and the Lick Observatories (36-in., f/19·3 refractor). Many of these photographs are readily available and catalogues are issued by the California Institute of Technology Bookstore, 1201 East California Street, Pasadena, California, and by the Royal Astronomical Society, Burlington House, London, W.1. A complete Lick photographic atlas may be obtained from The Sky Publishing Corporation, Harvard College Observatory, Cambridge, Massachusetts.

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See also: *text of Appendix I.*

APPENDIX II

List of Constants *

Periods

Sidereal Period of Moon = $27^{d}{\cdot}321\ 66$

Period of axial rotation of Moon = $27^{d}{\cdot}321\ 66$

Angles, etc.

Equatorial horizontal parallax of Moon, when at its mean distance from the Earth = $57'2''{\cdot}5$

Angular semi-diameter of Moon when at its mean distance from the Earth = $932''{\cdot}6$

Inclination of Moon's equatorial plane to the ecliptic = $1°32'$

Inclination of Moon's orbital plane to the ecliptic = $5°09'$

Inclination of Moon's equatorial plane to its orbital plane = $6°41'$

Lengths

Mean distance of Moon from Earth = 384 400 km (239 000 mls)

Equatorial radius of Earth = 6378 km (3963 mls)

Radius of Moon = 1738 km (1080 mls)
$\approx 0{\cdot}2725 \times$ (equatorial radius of Earth)

Eccentricity of orbit of Moon = $0{\cdot}054\ 9$

Masses, etc.

Mass of Moon = $0{\cdot}0123 \times$ (mass of Earth)

Constant of gravitation $G = 6{\cdot}67 . 10^{-8}$ cm^3 g^{-1} sec^{-2}.

Mass of Earth = $5{\cdot}98 . 10^{27}$ g

Mean density of Moon = $3{\cdot}34$ g cm^{-3}
$\approx 0{\cdot}6 \times$ (mean density of Earth)

Mean density of Earth = $5{\cdot}52$ g cm^{-3}

* *See* ALLEN, C. W., *Astrophysical Quantities*, Lond.

Acceleration due to gravity at the surface of the Moon
$= 162$ cm sec^{-2}
$\approx 0{\cdot}165 \times 981$ cm sec^{-2}.

Velocity of escape from the surface of the Moon
$= 2{\cdot}38$ km sec^{-1} ($1{\cdot}48$ mls sec^{-1})
$\approx 0{\cdot}213 \times$ (velocity of escape from the surface of the Earth)

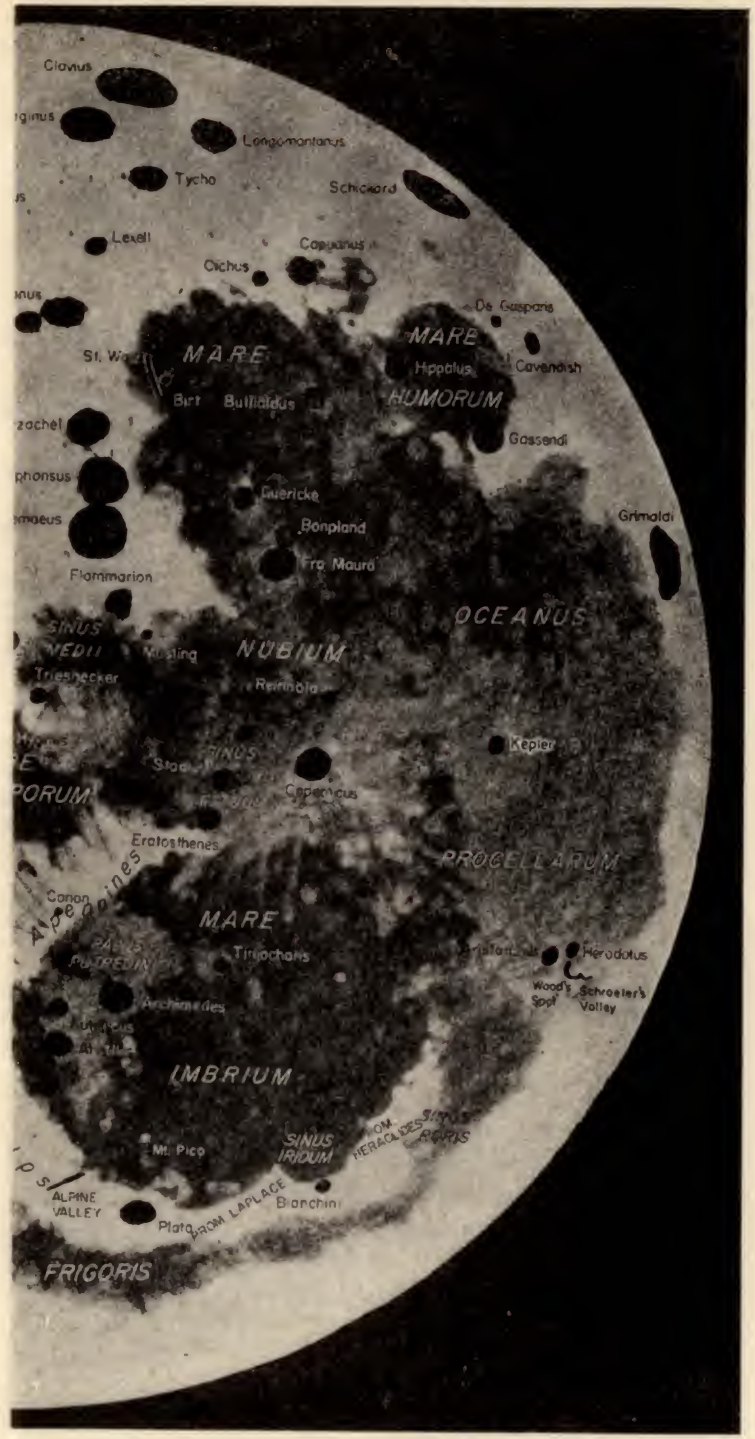
Velocity of escape from the surface of the Earth $\approx 11{\cdot}2$ km sec^{-1} ($7{\cdot}0$ mls sec^{-1}).

Circular velocity at the Moon's surface $= 1{\cdot}68$ km sec^{-1} ($1{\cdot}04$ mls sec^{-1}).

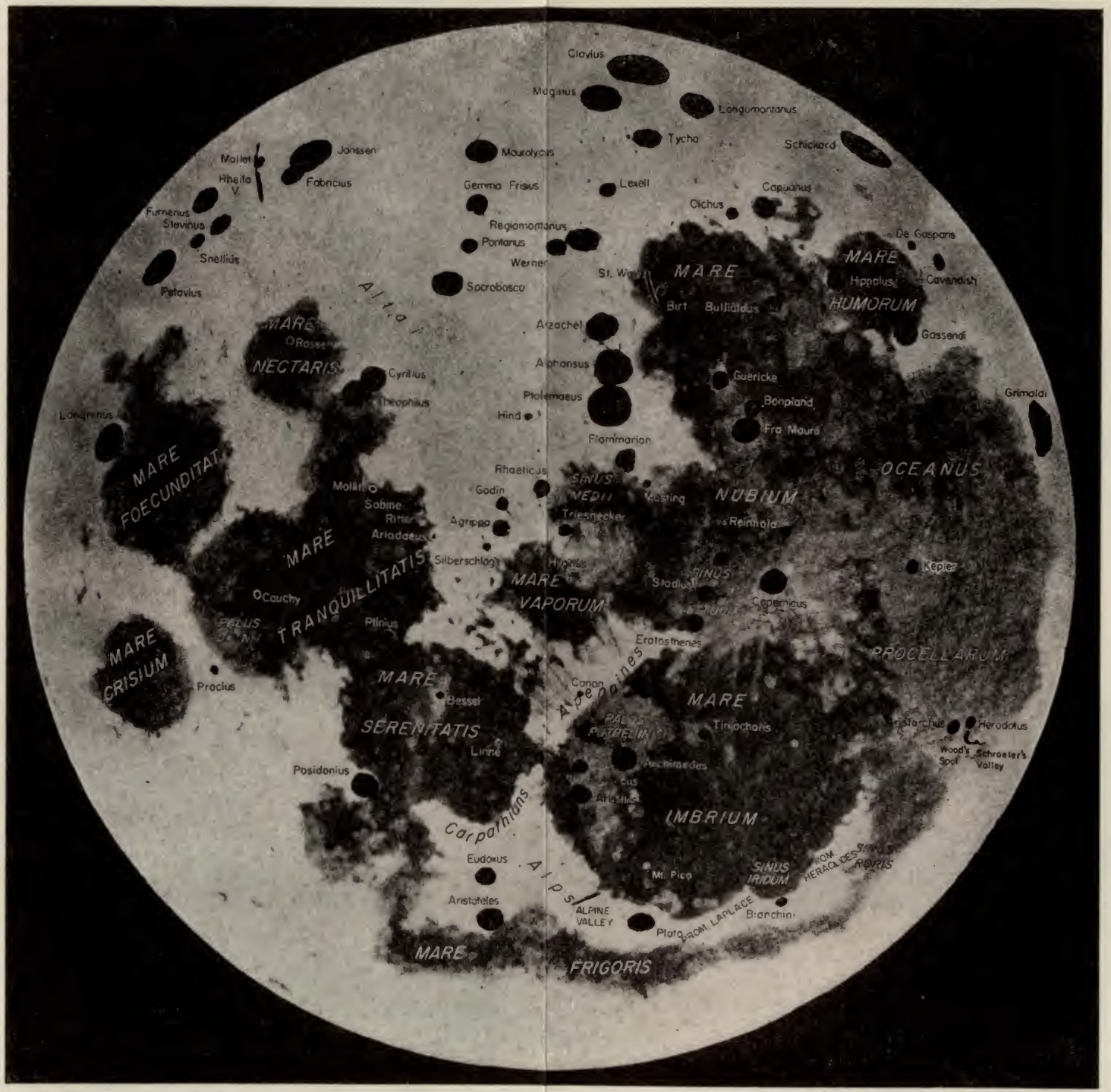
Brightnesses

Equivalent stellar magnitude of full Moon $\approx -12{\cdot}6$

Mean albedo of Moon $\gtrsim 0{\cdot}1$.



s of features discussed in the text



KEY CHART. The positions of features discussed in the text

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